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ABSTRACT

This publication reviews the potential hazards to the environment of weather modification techniques as they eventually become capable of producing large scale weather pattern modifications. Such weather modifications could result in ecological changes which would generally require several years to be fully evident, including the alteration of plant and animal communities by shifts in reproduction rates, growth, and mortality of weather sensitive species. The report includes sections on anticipated kinds of weather modifications; effects in semiarid climates and in humid climates; pests and diseases; direct effects of seeding agents; biology of lakes and streams; fog, hail, lightning, and hurricane modification; environmental monitoring programs; inferences from ecological theory; recommended research; and recommended pre-modification field surveys. [Not available in hardcopy due to marginal legibility of original document.] (PR)

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Ecological Effects of Weather Modification: A Problem Analysis

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WILLIAM C. JOLLY

May 1969

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U. S. Department of the Interior
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Office of Atmospheric Water Resources

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THE UNIVERSITY OF MICHIGAN
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SCHOOL OF NATURAL RESOURCES

Department of Resource Planning and Conservation

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ECOLOGICAL EFFECTS OF WEATHER MODIFICATION:
A PROBLEM ANALYSIS

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Sponsored By:

U.S. Department of the Interior
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. . . Science is the most powerful means we have for the unification of knowledge; and a main obligation of its future must be to deal with problems which cut across boundaries, whether boundaries between the sciences, boundaries between nations or boundaries between man's scientific and humane concerns.

. . . I would mention a problem which I know has greatly concerned many of you - that is, our responsibility to control the effects of our own scientific experimentation. For, as science investigates the natural environment, it also modifies it - and that modification may have incalculable consequences, for evil as well as for good.

In the past the problem of conservation has been mainly the problem of inadvertent destruction of natural resources. But science today has the power for the first time in history to undertake experiments with premeditation which can irreversibly alter our biological and physical environment on a global scale.

President John F. Kennedy
Address to National Academy
of Sciences
New York Times,
October 23, 1963

I. SUMMARY AND RECOMMENDATIONS

Weather and climate are major factors in human activity. Even where human communities have adapted themselves reasonably well to the climate of a region, temporary deviations from the normal -- severe storms, droughts, unseasonable frosts -- periodically cause acute monetary loss and personal suffering. Weather modification is thus an age-old dream. Research on atmospheric processes has apparently brought man to the threshold of realizing that dream, at least in part.

There is some evidence that within the next decade, precipitation can be modestly increased or decreased over selected target areas, hail and lightning reduced, and severe storms moderated. None of these are yet feasible on a broad scale, and they may never be. Practical weather modification, however, is sufficiently probable that substantial effort is justified to predict the potential social, economic, and ecological consequences if the technology should be fully developed. This report is intended to evaluate the changes in the structure, organization, and behavior of natural plant and animal communities likely to result from the kinds of deliberate weather modification, at a scale ranging from an individual cloud to a storm system, that appear worth serious consideration in the foreseeable future.

Weather modification provides, almost for the first time, an opportunity to judge beforehand the benefits and costs of an extensive deliberate alteration of the natural environment. A generation ago, a new technology such as weather modification would almost certainly have been applied as soon as it was available if it promised substantial monetary gains. Public attitudes toward man's environment are changing rapidly, and monetary returns alone may no longer suffice as a reason for introduction of a technology that could have pervasive effects on that environment.

Weather modification will be desirable only if: (1) The weather change results in a net economic gain to the community as a whole, with adequate compensation to those who suffer economic loss. (2) The weather change results in a net increase in psychological satisfactions gained from the weather, and from those components of the physical and biological environment affected by the weather. These satisfactions specifically include esthetic enjoyment by man of plant and animal communities affected by weather. How to equate psychic satisfactions against economic gain (worthwhile only as it produces psychic satisfactions) is no more solved today than it was in Jeremy Bentham's day. (3) Significant options previously available are not lost. Such lost options include extinction of plant and animal species, destruction of irreplaceable ecosystems or scenic wonders, and loss of valuable genetic material.

These conclusions contradict the view of some proponents of weather modification, that since Western civilization has been based on exploitation of resources and modification of the environment, any change is acceptable if present economic benefit can be obtained from it. These individuals point out that a technological fix has always been possible up to now whenever ecological trouble threatened.

Also rejected here is the viewpoint of some ecologists, whom social scientists (e.g., Wengert 1958) have accused of contending that sound resource use should be measured against the primeval conditions of 1492. ". . . In this view man is the despoiler of nature, and resources and their preservation become ends in themselves. To the social scientists, resources are a means -- a function of time, space, and culture . . . [The objective should be] the application of intelligence to current resource problems in the context of particular social conditions and objectives." The mere assertion that the environment is being changed or even damaged does not of itself justify social intervention to prevent or reverse the change. There is needed first an assessment of the magnitude of the damage, and of its political, economic, and other social costs; and then an exploration of alternative measures and devices for achieving similar ends (Barnett 1967).

GENERAL CONCLUSIONS

Ecological effects of weather modification will be the result of moderate shifts in rates of reproduction, growth, and mortality of weather--sensitive species of plants and animals. Ecological changes from the kinds of weather modification now visualized will seldom be sudden or catastrophic. Plant and animal communities change rather slowly in response to changed climate. The cumulative effect of slow year-to-year changes in species abundance could be a rather extensive alteration of original condition, but the alteration could take place almost unnoticed by the general public.

The combined effect of such stresses as air pollution, pesticide application, and other environmental changes may interact with weather modification in such a way that the total effect will be substantially greater than the sum of the individual, perhaps relatively small, alterations (109).[1/] The prospect of complex ecological interactions is one of the most important points to be considered in assessing the probable consequences of environmental change due to the activities of man.

Weather modification will be a change imposed on an already variable climate. This will make quick detection of its effects more difficult than if normal weather was identical from one year to the next. This problem will be accentuated by the normal, so far unexplained, fluctua-

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[1/] Numbers in parentheses refer to the pertinent pages in the body of this report.

tions in species populations of many plants and animals on a wide variety of sites (94), upon which changes due to weather modification will be superimposed.

This conclusion should not be confused with the fallacy that, because the change anticipated from weather modification is smaller than the normal variability of weather, weather modification will have little or no biological effect. It has been adequately shown that, except for some exceptional circumstances in particularly harsh climates, the long-term structure of plant and animal communities is a response to average climatic conditions, not to isolated events. An increase of 10% in mean annual precipitation will inevitably lead to an adjustment in community structure over a period of time, even if the normal year-to-year variation in rainfall is much greater, say 30%.

This adjustment will normally take place more slowly in a region of highly variable weather than in one of relatively uniform weather from year to year (112). Likewise, sensitivity to deliberate precipitation change is likely to be greatest in semiarid climates, least in humid climates, and intermediate in truly arid regions (113).

SPECIFIC ANTICIPATED EFFECTS OF WEATHER MODIFICATION

Populations of Plants and Animals

Organisms will in general respond to increased moisture as individual species, not as communities. In mountainous areas, there will not be a uniform downward migration of biological communities under the influence of artificially increased precipitation. Rather, at least some plants and animals will become regularly associated with species among which they were not commonly found in the past (110).

Changes in vegetation composition and structure will mostly be the result of changes in abundance of species already present in the area. Invasions by species previously unable to survive may occur, but such invaders are unlikely to build up to spectacular numbers. The appearance of a major invasion could be created, however, by multiplication of undesirable species previously present in such low numbers as to be relatively unnoticeable (111).

Major or catastrophic changes in insect abundance or in incidence of plant diseases are not likely from the kinds of weather modification now visualized. In part this is because most insect populations and plant pathogens are more directly affected by temperature and humidity than by precipitation. Outbreaks of a sort that are now occasionally triggered by unusual weather sequences may possibly be more frequent after weather modification (49). Weather modification is not likely to be very useful even as an auxiliary measure in pest control programs (51).

Insect populations, and perhaps other pests, are likely to show the greatest effect five to ten years after weather modification starts (depending on the length of life cycle of the organisms and their hosts). Plant biomass will build up first because of increased precipitation, leading to establishment of a new host-insect or host-disease equilibrium. A severe test of the stability of this equilibrium will come at times of drought (inevitable even with weather modification) following 5 to 10 years of increased precipitation.

Increases in weed abundance will probably be roughly proportional to the change in mean precipitation. Explosive multiplication of noxious weeds is unlikely as a consequence of weather modification. There may be exceptions to this statement, just as with insects or plant diseases, but the exceptions will be essentially unpredictable (62).

Large mammals, at least in North America, are unlikely to become extinct either totally or within a moderately large region as a consequence of weather modification. The number of large and small mammals could be reduced in some areas by loss of food or habitat or by increase of winter snow, but land management agencies would be able to provide habitat manipulation procedures adequate to maintain at least some members of the species even under altered weather. Such assurance cannot necessarily be given if weather modification is unwisely combined with other environmental changes, however(120).

Big game populations could be adversely affected if artificial increase of snowpack further reduces winter range, which is already critically short in many localities. Most contemplated snow pack modification programs will concentrate on the zones of deep snow abandoned by large animals during winter, but adequate control may not be attainable. In any case, there are grounds for believing that the first major ecological effect of weather modification likely to be detected, at least by the general public, is a change in wildlife population structure in certain critical localities. It is perhaps even more likely that weather modification will be widely blamed for real or imagined fluctuations in wildlife numbers, whatever their cause (34).

Ecological Change in Relation to Land Management

Moderately disturbed plant and animal communities will be more sensitive to weather modification than either essentially undisturbed stable communities or continuously disrupted areas such as cultivated fields and home gardens (115). Specifically, if precipitation is artificially increased over range lands, the effect on vegetation composition will be greater on lightly to moderately grazed range than on range that is either heavily grazed or not grazed at all (25).

Precipitation increase will change the species composition of grasslands primarily through increase in abundance of species formerly confined to wetter sites (23). A moderate increase in precipitation may bring about some decrease in populations of small mammals such as jackrabbits where grassland vegetation is already in generally good condition. On severely overgrazed range, herbivores may hinder vegetation responses to increased rainfall. Big game populations on rangeland can probably be somewhat increased by weather modification if proper livestock and wildlife management practices are followed (27).

Tree growth and growth of associated native vegetation may be somewhat stimulated through partial alleviation of summer water deficits. The precise nature of the effect will depend on when the artificial rain is applied in relation to the progress of the seasons and within the life cycle of individual species (42).

In regions receiving less than 12 inches of annual precipitation, an increase in rainfall will probably be accompanied by an increase in sediment yield. Above about 12 inches, upland erosion should decrease with increased precipitation. Channel degradation and accelerated sediment transport is likely from the lower reaches of rivers in semiarid areas as a result of weather modification (29). Changes in rainfall intensity may occur as a result of cloud seeding, and may alter patterns of infiltration and erosion (29). Leaching and loss of mineral nutrients from the soil may be accelerated by precipitation increase, particularly where the normal vegetation has been severely depleted in the past (46).

Wetlands will be affected by increased precipitation. The precise nature of the effect and its desirability or undesirability will depend on the local situation. Comprehensive studies of the hydrologic and ecological situation should be made in each specific area having significant wetland resources before weather modification is undertaken. This is especially pertinent with respect to coastal areas having salt marshes that might be affected either directly by increased precipitation or by runoff from adjacent land. Artificial increase of precipitation could help somewhat to alleviate the critical ecological situation facing Everglades National Park in Florida as a result of land drainage and diversion of flood waters away from the Park, but this will be only of limited and partial assistance. Reliance should not be placed on weather modification to solve the Everglades problem (45).

In the face of anticipated future demands for recreational fishing, any enhancement of freshwater fisheries, as a direct objective or by-product of weather modification, could be esthetically and economically important. Conversely, any loss of productive waters would not only be serious in its own right, but would seriously complicate the task of managing our remaining equatic recreational resources. Hydrologic changes resulting from weather modification may improve the physical environment for fish under one set of geologic and climatic conditions, and damage it under another. No easy generalization about benefits or losses are likely to be forthcoming, but it should be possible to predict the consequences of hydrologic change for individual streams or watersheds, given an adequate data base (74).

FOG, HAIL, LIGHTNING, AND HURRICANES

Fog dispersal, so long as it is confined to airports, roads, and other restricted localities where fog severely interferes with human activity, will have little ecological effect. If it should become feasible and desirable to change the fog climatology of broad areas such as the north coast of California, the ecological consequences would be profound. No irreversible ecological effects are foreseen from hail or lightning suppression (83).

Hurricane control, although very difficult to achieve, could drastically alter the water balance of the eastern seaboard of the United States, the Gulf Coast, and the Caribbean region. Appreciable reduction in frequency of hurricane winds could change forest structure in some localities, and might also affect some marine communities (85).

ECOLOGICAL EFFECTS OF SEEDING AGENTS

Silver is a potentially toxic heavy metal that will be introduced into the environment. Preliminary indications are that it will not concentrate to harmful levels through either terrestrial or equatic food chains. The threat of environmental contamination from silver iodide does not seem great enough to preclude its use at this time. Close attention should be given to the problem, however (64).

Fog dispersal agents may have detrimental effects on plants and animals over a long period. As a matter of public policy, aerial distribution of unknown proprietary compounds should not be allowed on any but a strictly experimental basis, even if tests convince health agencies that the materials pose no immediate threat to human welfare. Full disclosure of the composition of any such material added to the environment is necessary in order that the scientific community as a whole may evaluate the possible long term effects (73).

MONITORING THE EFFECTS OF WEATHER MODIFICATION

A program to monitor the effects of weather modification should be a part of a national (and indeed global) ecological survey and monitoring program. It would be wasteful and inefficient to set up separate programs to monitor ecological changes due to weather modification, pesticides, and air pollution, for instance, and yet this is the direction in which national policy appears to be headed (89).

Plans are not yet ready for implementing proposals for a national ecological survey. A comprehensive systems analysis of the entire problem should be initiated at once. It would emphasize both the institutional aspects, including management of the survey, interpretation of the results, and procedures for applying the results through the political process; and the technical biological aspects of collecting the data and interpreting them to predict ecological responses. This analysis could justifiably be financed from weather modification funds, but it should specifically be designed to include other aspects of environmental change as well as weather modification. The analysis should include, among other things:

- Purpose of ecological survey and monitoring program
- What is to be measured
- Who will use the resulting data, and in what way
- Relation to existing programs of state and federal agencies
    - (Examples: USGS Vigil Network; USFS Barometer Watershed program; ESSA Benchmark stations)
- Procedure
    - Standardization of measurement
    - Frequency of remeasurement
    - Statistical design and interpretation
- Who should do it
    - Agency responsible -- existing federal agency, or new independent group such as a National Ecology Institute
    - Requirements for technical manpower -- use of technicians versus highly trained specialists
- Lessons from similar programs in other countries
    - Particularly Australian Division of Land Research and Regional Survey, C.S.I.R.O. (Primarily a regional development survey, not an environmental monitoring program)
- Cost estimates, and cost-benefit relations
- Application of results

Field research, on a relatively limited basis at first, should be initiated to develop effective operational procedures for measuring relevant indicators of biological change on actual sample plots (103).

Pre-modification Survey

Approximately 10% of the budget for any large-scale pilot project in weather modification, such as is now planned for the Upper Colorado River Basin, should be allocated to a concurrent biological survey of the affected area, to identify and evaluate conditions likely to be significantly altered by a deliberate change in climate. Such a survey should be undertaken for exactly the same reason that the meteorological program is being carried out -- to develop and test procedures and techniques for use in an eventual operational program. If the prospects of deliberate weather modification are good enough to justify field operations on the scale of the proposed Colorado River Basin Pilot Project, they are good enough to demand expenditures to develop procedures for identifying in advance some of the possible social and biological consequences of this new technology (144).

ADDITIONAL RESEARCH REQUIRED

There has so far not been a single biological field study completed and reported in the literature specifically designed to identify any aspect of the ecological effects of weather modification. A recommendation for additional research is thus more than an automatic response. Research is needed in four specific categories: (a) large scale multidisciplinary investigations of ecosystem properties, to determine how ecosystems react to environmental stress, including the stress of weather modification; (b) research to develop effective procedures for monitoring the effects of environmental change, including weather modification; (c) relatively short term field and laboratory investigations to answer specific questions raised by the prospect of successful weather modification; (d) development of mathematical models of ecosystem behavior that will aid in predicting ecological effects of weather modification in advance of an operational program (123).

Support of Ecological Research

Agencies supporting research and development in the technology of weather modification have an obligation to support research to determine what the social and biological consequences will be if the technology they are sponsoring is perfected. In some cases at least they lack legal authority to do so. Congress and the Bureau of the Budget should insist that agencies sponsoring research in the physical science aspects of weather modification allocate funds to social and biological investigations related to weather modification.

The bureau of Reclamation, ESSA, and other agencies supporting research and development in the physical science aspects of weather modification should allocate a fraction of these research funds, on the order of 2%, to general support of research on ecosystem processes related to environmental change. The recommendation of some fraction of physical science research funds, rather than a fixed dollar amount based on identified needs, is not satisfactory, but it is difficult to see an alternative. Funding agencies are accustomed to allocating money for specific projects after weighing the value of the information against the cost of obtaining it, and then providing enough money to carry out the project. This is an appropriate pattern for some categories of weather modification research, but it is not applicable to multidisciplinary, multi-objective research on ecosystem processes, the results of which will be applicable to a wide range of environmental problems (125).

Experimental and Observational Investigations

Experiments involving application of artificial rain to specific ecosystems should be undertaken at an early date. These experiments could logically be undertaken in connection with the grassland research program of International Biological Program in eastern Colorado (126).

Additional water should be applied to replicated plots in a pattern that simulates the incremental precipitation likely to result from weather modification. Substantial engineering and construction problems must be solved.

Field studies are needed of the adaptations of individual plant and animal species to climatic conditions, especially near the limits of their ranges, and of the genetic structure of these populations in relation to their adaptation. Related studies of the responses of individual plant and animal species to simulated climatic variables should be carried out in controlled environment facilities ("biotron"). Caution is necessary in interpreting the results of these experiments, because of the integrated system nature of the response of natural plant and animal communities to weather (128).

Snowpacks

In view of the emphasis weather modification planning is giving to alteration of snowpacks, extensive research is needed on the present and anticipated distribution and properties of snow, and the influence of snow on plant and animal communities. This should include (a) development of efficient portable electronic equipment for measuring depth and water content of snow in place; (b) field observations and photogrammetric studies of snow distribution under various conditions of topography and total snowfall; (c) development of mathematical models of the distribution of snow in space and time as a function of topography, total snow amount, wind, solar radiation, temperature, vegetation, and other pertinent variables; (d) statistical studies of the data from the Cooperative Federal-State Snow Surveys, to establish regional patterns of snow depth in relation to total fall; (e) additional studies of animal behavior, particularly of big game animals, in relation to depth and character of snow (129).

Statistical Analysis

A small university research team should be engaged to make a preliminary national inventory of biological field data gathered by government agencies for administrative purposes, and to assess the desirability of an extensive statistical screening project to extract patterns from these relevant to predicting ecological effects of weather modification. Survey data collected over long periods of time using sampling procedures having a low level of repeatability are of value chiefly because of the large number of observations. Computer methods make it possible in some instances to extract meaningful patterns from noisy data. There is some question whether this approach will be worthwhile in the present case, but the possibility should be thoroughly investigated (138).

Computer Simulation

There is a need for additional research combining detailed field and laboratory investigations with computer models of the structure and function of ecosystems. Computer models are particularly well adapted to dealing with problems that are presently beyond the range of analytical solution because of their size and complexity, or because they cannot be solved in the time available by experimentation on real systems. Ecological problems typically have both these characteristics (131).

An important use of system models is the determine the relative sensitivity of the system to variations in specific inputs. Sensitivity analysis can help to suggest limits within which precipitation can be varied without causing appreciable change in system performance, for instance. Computer models are particularly useful for helping to select the most relevant field experiments from the multitude that might be undertaken.

Among the existing computer simulation models likely to prove most useful for preliminary analysis of some of the possible effects of weather modification are the Stanford Watershed Model, which imitates the behavior of small stream basins under varying inputs of precipitation, solar radiation, and other climatic variables; and a simulation of transpiration and soil moisture relations being developed at the University of Michigan to evaluate the disposition of precipitation by vegetation and soil at a given point. These models are primarily useful for identifying sets of climatic, soil, and vegetation conditions likely to be particularly sensitive to climatic change, in contrast to those that are relatively insensitive. Several classes of modeling effort should be supported from weather modification funds.

Management Alternatives

Operational weather modification agencies should from the beginning support research to develop optimal strategies for incorporating weather modification into the total mix of resource management tools. If the technology should be fully developed, weather modification is likely to be applied without much regard for alternative means of achieving the same end. Review of alternatives is not generally encouraged under the existing American political system, where one group in society may be interested primarily in pushing weather modification and another in promoting transbasin diversion, for instance (140).

Ecological Education

Perhaps the most serious obstacle to successful collection and interpretation of the research data called for in this report is the shortage of properly educated people and of institutions equipped to carry out the research. Few universities are now educating students to make effective use of the analytical tools necessary to deal with man-dominated ecosystems. Emphasis in ecology has traditionally been on natural communities and on observational techniques. Institutions having the necessary research competence are for the most part already working to the limit of their capacity. This constraint affects the study of all forms of environmental change, not weather modification alone. Under present conditions, it is unlikely to be overcome except through an extensive federal training grant program of the type that has been so successful in developing technical staff in medical research. There is yet no equivalent Congressional pressure for education to deal with ecological problems of environmental quality.

EPILOGUE

The underlying theme of this report is the need to apply human technology for the real long-term benefit of mankind. Those concerned with developing and applying the technology of weather modification could well consider the words of Rene Dubos, expressed in his recent book "So Human an Animal": "In science as in other human activities, the speed of progress is less important than its direction. Ideally, knowledge should serve understanding, freedom, and happiness rather than power, regimentation, and technological development for the sake of economic growth. Emphasis on humanistic criteria does not imply a retreat from science; rather it points to the need for an enlargement and a rededication of the scientific enterprise. Scientists must give greater prominence to large human concerns when choosing their problems and formulating their results. In addition to the science of things, they must create a science of humanity, if they want the intellectual implications and practical applications of their efforts to be successfully woven into the fabric of modern life."

II. THE SCOPE OF WEATHER MODIFICATION

Deliberate weather modification is likely to be attempted when potential beneficiaries foresee benefits to them, and perhaps to the community at large, in excess of their own costs. In this respect it is similar to application of pesticides and other agents whose ecological effects are attracting increasing public attention. Weather modification differs from pesticide treatment, however, in that there is no feasible way even in principle to confine application to a single land ownership, type of land use, or ecological community. It is inevitable that effects of weather modification will extend to others than those directly responsible for initiating it.

The fact that weather modification will be applied in anticipation of direct economic gains likewise distinguishes it from such environmental changes as air pollution. The latter, although its effects also usually extend beyond the jurisdiction of those directly responsible, occurs because the cost of prevention is deemed to outweigh the losses incurred, not because anyone perceives a positive social benefit from polluted air.

Social and institutional constraints, as well as technological problems, suggest at least three time scales at which planned weather modification programs are likely to become operational. Some are already technically, and perhaps economically, feasible or show promise of becoming so within five years. Others are more problematical, but may be effective by about 1980. Still others, mostly involving major interference with the general circulation of the atmosphere or the oceans, and resulting in alteration of the overall climate of entire regions, are farther off. These more distant programs, which would open a range of social, economic, and biological consequences staggering to contemplate, are specifically excluded from this report. The present status of weather modification, the statistical difficulties in evaluating its success, and some of the political issues involved in its eventual control, are well discussed in a non-technical article by MacDonald (1968). Other authoritative discussions are those by Houghton (1968) and the RAND Corporation (1969).

Principal economic objectives of kinds of weather modification that may be feasible, at least on a pilot basis:

(1) Within the next five years (in approximate order of feasibility and importance)

  a. Reducing air traffic delays by clearing fog from airport runways.

  b. Increasing runoff, either from rain or melting snow, into water supply and power reservoirs.

c. Augmenting precipitation in agricultural areas, either to increase production from present cropping systems or to permit growth of more profitable crops not now adapted to the area.

d. Reduction of hail damage to crops and property.

e. Augmenting precipitation over managed range and forest areas to stabilize or increase production of livestock or wood products.

f. Reducing incidence of lightning-caused forest fires.

g. Aiding in prevention and control of forest fires by stimulating precipitation over dry forests in advance of ignition, or over fires in progress.

h. Increasing snowfall in the immediate vicinity of commercial ski areas.

(2) By about 1980

a. Reduction of wind and flood damage from hurricanes and other large tropical storms by lowering their intensity, or, less probably, by "steering" them away from populated areas.

b. Reduction of damage from tornadoes and other severe storms.

c. Reduction in severity of snowstorms over densely populated regions, such as the Great Lakes shoreline, and diversion elsewhere (as to the New England-Quebec ski area).

d. "Convenience" control: reduction of rainfall on weekends for the benefit of outdoor recreation, or at other critical times for the construction industry, etc.

e. Use of programmed rainfall patterns as an auxiliary tool in control of insect pests, plant diseases, and human epidemics, or as an aid in air pollution control.

This is not a forecast that such operations will indeed be undertaken. The objective of this report is rather to evaluate what is likely to happen to plant and animal communities of interest and value to man if the postulated kinds of planned weather modification should become technologically feasible and economically attractive, and to demonstrate how ecological knowledge can help in incorporating weather modification into a strategy for managing the environment to yield maximum social and esthetic, as well as monetary, satisfactions to mankind.

KINDS OF WEATHER MODIFICATION THAT MAY BE WORTH SERIOUS CONSIDERATION BETWEEN NOW AND 1980

Meteorological factors set limits to the kinds of weather modification that need to be considered. The following statements are based on discussions with meteorologists at National Center for Atmospheric Research and ESSA Research Laboratories, both at Boulder, Colorado; Office of Atmospheric Water Resources, U. S. Bureau of Reclamation; and elsewhere.

Area of Treatment Units

Weather modification at the scale presently contemplated involves treatment of individual storms or storm systems ranging in area from a few square miles to a few hundred.

Effects on Precipitation

Mean annual or seasonal precipitation over treatment areas may be increased by 5% to perhaps 20%. It is unlikely that average increases of more than 25% can be achieved.

Suitable air masses or storms must be present for cloud seeding to be effective. Weather modification will neither prevent nor end a drought resulting from continental or regional weather patterns. For the same reason, precipitation will not normally be induced during seasons when it ordinarily does not occur. There is no likelihood of creating appreciable summer precipitation in the Mediterranean climate of California, for instance.

Year-to-year or season-to-season variations in precipitation may be altered by choice of treatment strategy. Depending upon management objectives, it may be decided to seed in some years and not in others, or in some seasons and not in others. Even within the same area, preferences for years and seasons of treatment may differ among potential beneficiaries.

The mix of suitable and unsuitable storm events in a given year or season largely determines how much effect cloud seeding is likely to have on precipitation during the period. According to the Office of Atmospheric Water Resources, U. S. Bureau of Reclamation (Patrick Hurley, personal communication), preliminary evidence indicates that cloud seeding achieves greater results from storms yielding relatively little natural precipitation than from storms which already produce high precipitation. These results suggest that man has the best opportunity for altering natural processes at times when nature is inefficient in producing rain or snow. If this conclusion is borne out by further research, the greatest effects of precipitation modification will presumably be registered in low rainfall years. Other meteorologists believe, however, that the opportunity for precipitation augmentation is more or less proportional to the size and number of naturally occurring storms.

Modification of the drop-size spectrum is an important aspect of cloud seeding. In some instances, particularly in warm clouds, drop size and resulting rainfall intensities might be increased to enhance total yield. In other instances, drop size and intensity may be reduced even if the total amount falling during a storm increases.

Massive overseeding can generally reduce the amount of rain below that which would otherwise fall, except perhaps in the case of very large frontal systems which overwhelm any practical effort at treatment. These are the storms generally responsible for widespread floods. It might be possible, however, to reduce the amount and intensity of convectional storms that produce local flash floods in the West, if these storms could be identified in time.

Temperature, Solar Radiation, Cloudiness, and Humidity

Temperature, mean cloudiness, and solar radiation are unlikely to be much changed by the kinds of weather modification now contemplated. These climatic features are primarily governed by the general circulation of the atmosphere. Present weather modification techniques are aimed at altering microphysical precipitation processes within clouds, and are expected to have little or no effect on the general circulation. Temperature and relative humidity will be altered appreciably only during the short period when additional water resulting from cloud modification is evaporating.

Hail

Frequency and destructiveness of hail can be reduced by artificial seeding if hail-producing clouds can be identified in time and if seeding equipment is quickly available. Equipment costs will probably confine operations to regions of frequent damage. There is no evidence so far that rainfall has been decreased by hail suppression tests involving normal seeding rates; there is evidence for modest increase of rainfall from cloud seeding for hail suppression (Schleusener 1968).

Fog and Stratus Dissipation

Supercolled fog and low stratus, which occur only in winter in the U. S., can be dissipated; this is routinely done at many airports. Dissipation of warm fog and stratus is technically more difficult, requiring extensive and sometimes repeated aerial distribution of the dispersing agent, and is likely to be practiced only in the immediate vicinity of heavily used airport runways. Substantial increase of summer sunshine by cloud dissipation is not likely to be practical.

Snow

Snow accumulations can be increased by seeding in appropriate circumstances. Snow management is most likely to be emphasized in areas tributary to water supply and power reservoirs in mountain regions.

Heavy snow storms, especially over populated areas, may possibly be dispersed over a wider area through seeding treatment that induces the snow to begin falling earlier and to last longer along the storm track. This might prevent the deep snow accumulations that are often locally destructive, as along the south side of the Great Lakes. It is unlikely that much can be done to mitigate effects of severe blizzards on the western plains, where the damage may be more from cold and wind than from the actual quantity of snow.

Lightning

Lightning may be decreased, particularly over mountainous forested regions where it is a major cause of fire. It is not clear whether change in precipitation amounts will be associated with a lightning reduction effort.

Hurricanes

It may eventually be possible to reduce the peak wind intensities in hurricanes. This is not yet possible, but it is reasonable to assume that appropriate technology will be available by 1980. Alteration of wind fields will strongly affect the closely associated precipitation patterns of tropical storms.

Effects at a Distance from the Target Area

Several questions with respect to downwind effects of cloud seeding remain unanswered. There is some evidence that nucleating agents or their effects may be carried 100 or more miles downwind, possibly producing unintended precipitation increases at a distance from the target. There is also the possibility that causing precipitation to fall more heavily over one area may reduce precipitation downwind by removing moisture from the air. It appears

that if such an effect does occur, it will not be a one-for-one replacement. The limiting factor in precipitation is most often lack of a lifting or cooling mechanism, and occasionally lack of adequate nucleating agents. Only rarely is the water vapor in the atmosphere insufficient for precipitation. There are indications that the reduction in water vapor content of the lower layers of the atmosphere as a result of cloud seeding is too slight to cause significant precipitation reduction downwind. The best that can be said at present is that, while off-site effects on precipitation may occur, they will be small in comparison to effects over the target area, and may not necessarily be negative.

Irreversible Effects

Anticipated cloud seeding systems are not likely to get out of control. There is little indication that major irreversible or cascading effects on atmospheric processes would take place. The chief possible exception is a postulated effect on the general circulation of the atmosphere resulting from a change in the energy absorbing and reflecting characteristics of a major segment of the earth, as through a substantial increase in extent of winter snow cover over the northern hemisphere (Fletcher 1968).

DELIBERATE AND INADVERTENT CLIMATIC CHANGE

Alteration of weather brought about by cloud seeding or other deliberate interference with atmospheric processes will necessarily be superimposed on other, inadvertent, climatic changes due to natural or manmade causes. The existence of inadvertent climatic change will make it more difficult to assess the reality of planned weather modification; claimed effects may in fact be due to other causes. Furthermore, the ecological effects of a planned weather change may be partially masked by unanticipated changes in other climatic variables.

For instance, there is evidence of a progressive increase in atmospheric turbidity over the last 10 years, seemingly due to manmade atmospheric pollution (Peterson and Bryson 1968). This could reduce the amount of solar radiation reaching the earth's surface enough to lower the mean temperature. Increase in atmospheric carbon dioxide content, mostly from burning of fossil fuels, may at the same time be increasing temperatures through the so-called "greenhouse effect". These two influences seem to be largely counteracting each other at present, but if one or the other were to become dominant, increased temperature would partially offset the ecological effects of additional precipitation, whereas decreased temperatures would accentuate them.

Increase in atmospheric aerosols, including lead iodide from automotive exhausts, industrial emissions, and smoke from forest fires and other organic combustion, may significantly alter precipitation processes (Schaefer 1969).

WEATHER MODIFICATION AND ECOSYSTEMS

Any recognizable unit of landscape includes a variety of plants and animals living together, competing, and interacting with each other and with their environment. Such an association of plants and animals, together with the non-living topographic, soil, and climatic factors that circumscribe their existence, is an ecosystem. Man is an essential component of practically all ecosystems, and there are few that have not been appreciably altered by man's activities. The spectrum of change extends from the artificiality of large cities and intensively cultivated rice paddies to wildernesses almost untouched by man.

This report does not aim to make value judgments, but to provide information for use in the political process of making decisions about use of weather modification. Ecological knowledge has not yet reached the stage where reliable predictions can be made of the probable effects of specific changes in environmental variables on plant and animal communities. Because of the inherent variability of ecological processes, it is unlikely that strictly deterministic predictions of this sort can ever be made. However, a great deal of information has been collected in the last sixty years on the relations between organisms and environment. These data have not generally been organized into predictive models useful for assessing the effects of environmental change on whole ecosystems. This now appears possible, at least in a preliminary way. The resulting models can then be used to guide additional field and laboratory research. Weather modification is a valuable case study to point the way toward better procedures for predicting the impact of other modifications of environment. The methods used in successfully predicting how ecosystems will respond to alterations in weather or climate should be adaptable to predicting some of the consequences of man's other activities on land and in the oceans.

ORGANIZATION OF STUDY

There is an extensive body of literature on the effects on plants and animals of microclimatic changes induced by agricultural and forestry practices, by urban construction, and other small scale environmental alterations. There have been few serious efforts until now to assess the potential ecological effects of weather modification at the scale of individual clouds and storm systems, in part because the likelihood of successful weather change seemed so remote that the subject was hardly respectable. In 1965, the National Science Foundation Special Commission on Weather Modification asked the Ecological Society of America to organize a panel to review weather modification in the context of biological communities. The group convened for some three days and prepared an evaluation which was accepted in part by the Special Commission. The complete report of this group has since been published (Ecological Society of America 1966).

The present report began as a contribution to the work of the Task Group on Human Dimensions of the Atmosphere, convened under National Science Foundation sponsorship by National Center for Atmospheric Research, Boulder, Colorado. This Task Group included representatives from the fields of economics, geography, sociology, political science, law, ecology, and meteorology. Its objective was to identify specific areas for research in human uses of the atmosphere and to foster and stimulate interest in these problems among social and physical scientists. The final report of this Task Group (Sewell 1968) includes a recommendation for evaluation of the ecological problem in greater detail.

The present report was undertaken with funding from the Office of Atmospheric Water Resources, U. S. Bureau of Reclamation, Denver, Colorado. Active work on the study began in late May, 1968; the final draft was completed in April, 1969. It was prepared primarily by the project director, Charles F. Cooper, who devoted approximately half time to the enterprise over the life of the project, and the assistant director, William C. Jolly, who was employed full time.

To ensure that adequate coverage was given to the whole range of significant fields, consultants were employed to assess problems in entomology, plant pathology, range management, paleoecology, aquatic biology, and systems analysis. Personal discussions were held with each consultant, and each prepared a report to the project director dealing with his own area of competence. These individual reports were woven into the general text, in most cases without specific acknowledgement. The several consultants each had the opportunity to review pertinent sections of the final draft, but they are not accountable for errors, omissions, or false interpretations.

The entire manuscript was reviewed by R. H. Whittaker of Cornell University. A member of the original Ecological Society panel on weather modification, he has worked in both plant and animal ecology, and is one of the few ecologists with formal publications dealing with ecological effects of weather modification (Whittaker 1967a).

In addition to those formally employed as consultants, many land managers and ecological researchers were interviewed in person or by correspondence. No effort was made in this study to carry out original field research. The report is based entirely upon a review of the literature and upon experience and observations of men in the field. An extensive body of literature was reviewed, but the material reported here is intended to be illustrative rather than exhaustive.

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III. PRECIPITATION MODIFICATION IN SEMIARID AND ARID REGIONS

Semiarid and arid regions are arbitrarily defined here as those regions where crop production is normally carried out either under irrigation or with specialized dry farming techniques. The water used by industries, municipalities, and agriculture in arid and semiarid regions comes largely from mountains, adjacent or at a distance. Weather modification may be attempted in these source areas to augment downstream runoff, hence they are included here even though the climate of mountain snow zones might properly be classed as humid. This discussion, then, deals with the United States and adjacent Canada west of about the 98th meridian, except for part of the Pacific Northwest.

Weather modification in this region will probably be aimed initially at increasing the accumulation of snow at higher elevations, to augment runoff into streams and water supply reservoirs. Present indications are that proper selection of seedable storms (probably on the basis of cloud top temperature and wind direction), and efficient delivery mechanisms for the seeding agents, may make it possible to increase snowfall substantially in parts of the Rocky Mountains and the Sierra Nevada.

Efforts may also be made to increase local precipitation at lower elevations for the benefit of dryland agriculture, livestock grazing, and forest production. This might be achieved either through increased winter precipitation, which adds to the reservoir of soil moisture that can be drawn on during the growing season, or from added rainfall during the growing season itself.

In the vast region considered here, there are several rather distinct types of ecosystems, each of which will react differently to weather modification. The major groups will be discussed separately.

GRASSLANDS OF CENTRAL NORTH AMERICA

The grasslands of central North America range from the true prairie of the midwest to semiarid shortgrass plains. In general, height of grasses and total production of plant material decrease westward along the rainfall gradient. Soil moisture, resulting from the interplay of precipitation and transpiration, largely determines the structure and species composition of the grassland communities. The grassland in any one area is a complex pattern of different combinations of grasses and other species, in response to local variations in slope, exposure, soil, and other environmental variables.

Natural Variations as Simulators of Weather Modification

The decrease in precipitation during the great drought of 1934-40 was much greater than any change likely from intentional weather modification, yet the responses to drought and to renewed precipitation at its end are among the most useful data for the present analysis. Because of lack of moisture, the native dominants in the true prairie of Kansas and Nebraska, principally little bluestem *(Andropogon scoparius)* and big bluestem *(A. gerardi)*, decreased greatly in abundance. They were largely replaced by grasses of drier climates, such as blue grama *(Bouteloua gracilis)* and western wheatgrass *(Agropyron smithii)*, which normally formed a large part of the mixed prairie vegetation to the west. Mixed prairie moved 100 to 150 miles east of its normal range into central Kansas, eastern Nebraska, and eastern South Dakota (Weaver 1961). This was in no sense a total replacement; the invading species had already been present as a minor component of the true prairie, particularly on dry sites. And the bluestem, apparently dead, proved still viable when the drought broke.

The first response to renewed rainfall in 1941 was exuberant growth of the newly established western species. Two to three years later, crowns and rhizomes of the surviving bluestems had broken dormancy almost everywhere. The patches of blue grama established during the drought were invaded by big bluestem. Rhizomes advanced under the blue grama sod; the grama stands became thinner and the individual plants more attenuated as the tall competitor grew more abundant. Finally only decaying remains of dead blue grama plants remained in the shade of the flourishing bluestem (Weaver 1961).

The drought, and community deterioration, were less severe in the mixed prairie of Saskatchewan than in the tall grass prairie studied by Weaver. Vegetation had essentially fully recovered by the middle 40's when several areas were sampled in detail (Coupland 1959). Precipitation in the years 1950-54 was about 20% above the long term average. Species composition had changed appreciably by the end of that period. Blue grama declined from about 43% to 31% of the percentage composition in the sampled stands, while the taller *Stipa spartea* and *Agropyron* spp. (mostly *A. dasystachyum)* about doubled in abundance. *Stipa comata* decreased to about half its former proportion in the stand. It thus seems that a single area of grassland in the northern Great Plains might change from *Bouteloua-Stipa* to *Stipa-Bouteloua* to *Stipa-Agropyron* (with displacement of *S. comata* by *S. spartea)* during an extended period of precipitation artificially increased above the previous mean.

These and other studies of grassland response to weather suggest that perennial species not already present in the area are unlikely to become important components of grassland vegetation as a result of a 20% increase in mean annual precipitation. Rather species previously confined to the moistest sites in the vegetation mosaic will increase their abundance.

Resistance to Change

Several self-regulating mechanisms might restrict the shift in grassland community boundaries resulting from added rainfall. The first is degree of efficient occupancy by species liable to be displaced. Whereas the invading blue grama almost disappeared from true prairie soon after the drought ended, western wheatgrass remained much longer (Weaver 1961). Wheatgrass replacement began when the revived big bluestem crowns sent up scattered shoots throughout the wheatgrass sod; shoots from bluestem rhizomes appeared only after 2 or 3 years. Rhizomes extended outward to form circular patches 3 to 4 feet in diameter. Eventually these patches coalesced and surrounded the remaining wheatgrass. Replacement of wheatgrass seemed largely due to shading. Western wheatgrass grown rapidly in spring and early summer. Even in years of normal rainfall, it often depletes the soil moisture before tall grasses like bluestem begin their major growth. This growth pattern allowed it to persist for some time after the drought broke. A similar lag effect may delay the adjustment of other species to new conditions created by weather modification.

Genetic variation within species is another mechanism that may reduce the apparent or readily visible change in species composition of grassland vegetation. Natural selection has tended to produce genetic variants, or ecotypes, in many species. Ecotypes that look superficially alike may be adapted to different sets of topographic moisture conditions. Weather modification is likely to cause some ecotypes to replace others. There is apparently enough genetic variability in many grassland plants to allow at least some compensation of this sort.

Intensity of grazing will also modify the response of grassland communities to precipitation change. Loss of production and changes in species composition after onset of drought were more severe in heavily grazed areas, and the process of recovery from extreme drought was greatly lengthened by overgrazing (Albertson et al 1957). Furthermore, selective use by livestock tends to reduce the diversity of species composition. Ungrazed relic areas in the shortgrass plains of Wyoming exhibit very different species composition on bottomlands, swales, uplands, and north and south slopes; grazed portions of the same region are much more uniform (Beetle 1952). Moisture-demanding grasses that might find a new environmental opportunity as a result of moderately increased precipitation in the absence of grazing will have more difficulty getting a foothold where grazing pressure is heavy. On the other hand, opportunities for accelerated weed growth are greatest where heavy grazing has reduced competition from native species.

Where cattle were allowed to remove no more than 30 percent by weight of the current annual growth of shortgrass range in Colorado, distinct patches of grazed vegetation were surrounded by areas of essentially unused plants. Under moderate grazing which removed 40 percent of the current growth, a similar mosaic developed, but with patches of almost unused grass imbedded in a matrix of grazed vegetation. Still heavier grazing resulted in uniformly close cropping of the entire area. Heavily grazed blue grama plants declined in vigor, size, and vegetative growth. On the other hand, ungrazed blue grama clumps that had grown luxuriantly early in the season died during extended periods of hot, dry, weather, apparently because available soil moisture had been exhausted (Klipple and Costello 1960).

These observations suggest that the maximum effect of a modest increase in mean annual rainfall will be on moderately grazed range. On heavily used areas, developing seedlings will soon be cropped and only the plants most resistant to grazing will remain. If livestock are excluded completely, grasses grow so vigorously that their extensive root systems utilize most available moisture; moisture is often insufficient even for established plants when they grow too large. There is little chance for new species to become established. The mosaic pattern of moderately used range, however, may provide a greater variety of opportunities for growth of newly favored species than either heavy grazing or no grazing.

Succession and Natural Variation

Increased rainfall will accelerate plant succession and stimulate recovery of formerly overgrazed range. In the early years of the Soil Conservation Service, Booth (1941) noted that plant succession on abandoned cropland was greatly speeded by terracing, particularly if the terraces remained unbroken for several years. The terraces, which retained local rainfall behind dikes instead of allowing it to flow away, had much the same effects as augmenting the total fall. Similarly, Costello (1944) estimated that in eastern Colorado, a natural increase in rainfall of 2 to 3 inches between April and September is sufficient to double the rate of succession on abandoned cropland. A deficiency of the same amount persisting over a decade retards succession to the extent that double or triple the ordinary time is required to reach a given stage of successional development. Normal precipitation from April to September is about 7 inches in this area, so that the postulated change is somewhere between 25% and 45% of the growing season moisture supply.

Local soil and topographic influences may override precipitation patterns as a determinant of the vegetation mosaic. Hadley and Bucos (1967) observed a threefold difference in green herbage production among six community types in one 800-acre prairie in eastern North Dakota. The differences in species composition and the mosaic pattern were the result of complex interactions among topographic position, soil depth, salinity, and biotic responses to these conditions. A change in precipitation regime is likely to modify the influence of topographic position and soil depth on vegetation more than that of salinity.

Normal (meaning unexplained) variation in species composition may temporarily mask the effect of artificial precipitation increase on grassland vegetation. As only one of many examples, Penfound (1964) has reported sharp annual fluctuations in the botanical composition of prairies in Oklahoma which cannot be correlated with presently known combinations of climatic factors.

Seasonal Precipitation Patterns

An appreciable change in the season of rainfall will directly affect grassland vegetation. Bluebunch wheatgrass *(Agropyron spicatum)* is highly sensitive to early summer moisture stress when grown in competition with the introduced annual cheatgrass *(Bromus tectorum)*. Cheatgrass seedlings have a sufficient competitive advantage over wheatgrass seedlings throughout most of the Intermountain and Columbia Basin regions that the perennial is generally unable to reestablish itself naturally in areas from which it has been eliminated by past disturbance. However, a change in one factor, summer precipitation, destroys the competitive advantage of *B. tectorum*. If there is significant rainfall in June, wheatgrass seedlings can survive their critical first year; otherwise, they cannot (Harris 1967). However, another annual brome, *B. japonicus*, matures about three weeks later than *B. tectorum*. The latter species has decreased and the former has increased around Hays, Kansas. Evidently the higher proportion of summer rain in Kansas than in the Great Basin, where *B. tectorum* is abundant, tends to favor *B. japonicus* because of its later maturity (Hulbert 1955). Increased summer rainfall might tip the competitive balance between *B. tectorum* and *Agropyron* in favor of the latter; on the other hand, it might lead only to replacement of *B. tectorum* by *B. japonicus*. Since seedable air masses are rare in the Great Basin in early summer, it is unlikely that weather modification will produce the substantial increase in summer rain needed to favor bluebunch wheatgrass in that region. Artificial increase of summer rain in the Great Plains could, however, shift the zone of cheatgrass abundance somewhat to the west.

Changes in Animal Populations of Grasslands

Insects, noxious and beneficial, are sufficiently sensitive to weather that they are likely to be affected by weather modification (Chapter V). Large and small mammals are also likely to respond to weather modification.

Populations of black-tailed jackrabbits *(Lepus californicus)* in western Kansas are closely correlated with weather, increasing markedly in dry years (Tiemeier et al 1965). Jackrabbits in western Kansas increased during the 1952-56 drought. The apparent fluctuations in population may have been due as much to concentration as to actual increase or decrease in numbers. In dry years the animals gathered near food sources, where they were more readily observed. Absolute numbers did, however, sharply increase during the worst drought year, 1956. When renewed rainfall stimulated growth of dense weeds, jackrabbits declined. "The only explanation we have for the decrease in population is that the green, tall vegetation during years of normal and above normal rainfall may be less suitable for jackrabbits" (Tiemeier et al 1965). Other observers (Brown 1947) have suggested that jackrabbits increase on drought stricken areas because of the predominance of succulent small forbs; the short turf which permits quick escape; and the scattered residual bunches of vegetation which furnish protection.

All this indicates that a moderate increase in rainfall will probably result in lowering of jackrabbit populations where the vegetation is in generally good condition. On severely overgrazed range, however, it is not unlikely that the first effect of additional rainfall will be accelerated growth of weedy forbs, preferred by both jackrabbits and grasshoppers. These herbivores may become abundant enough to hinder vegetation responses to increased rainfall on overgrazed range.

There is little information on which to base predictions about the effects of weather change on other small mammals in the grassland region. Koford (1959) concluded that there is essentially no basis for statements about direct effects of weather fluctuations on the welfare of prairie dogs. Prairie dog abundance is so strongly governed by cultural factors, including grazing practices and poisoning programs, as to mask weather effects.

Large Mammals and Forage Condition

Numbers of white-tailed deer on the Edwards Plateau of Texas are closely related to precipitation. Mean population densities are primarily determined by average annual rainfall through its influence on vegetation. Year-to-year fluctuations around these mean densities reflect changes in annual precipitation (Teer et al 1965). Deer populations decrease from 10-15 deer per 100 acres in the eastern part of the Plateau, which receives about 32 inches precipitation per year, to less than 2 deer per 100 acres 400 miles to the west, where annual precipitation is only 12 inches. Population densities in a given year are everywhere closely related to the preceding year's precipitation. The relationship was closest during the severe drought years 1953-56, and somewhat less marked after rainfall returned to normal.

The whole Plateau is heavily used by sheep, goats, and cattle as well as by deer. Despite overuse of the range, deer are as abundant throughout as the vegetation will permit. "I believe that the densely populated range in the [Llano] Basin has the highest density of white-tailed deer of any area of similar size in North America" (Teer et al 1965). This seems to be one of the relatively few well established cases where numbers of large mammals are directly governed by available forage, which in turn is regulated by annual precipitation. This portion of Texas has a climatic and soil regime highly sensitive to precipitation -- practically all of any increase in rainfall is used for transpiration and plant growth. If present patterns of range use are maintained, any artificial increase or dedecrease of precipitation is likely to be directly reflected in numbers of deer. Elsewhere the relation will seldom be as close. Even on the Edwards Plateau, deer populations respond less to increased rainfall in years of above normal precipitation.

It is not likely that animals like pronghorn antelope will be as greatly affected by range condition changes brought about by weather modification as will deer. Pronghorns are less adaptable than deer, and their abundance today is governed more by human activities and management practices than by weather.

Drought and Its Alleviation

Severe droughts are a significant feature of many climatic regions. The Council of the American Meteorological Society (1968) has stated, " . . . cloud seeding can neither produce nor terminate droughts. Such conditions are associated with persistent patterns of air motion which inhibit the formation of clouds and precipitation. Clouds must be present for the occurrence of natural or manmade precipitation." This casts doubt on the conclusion of the Ecological Society of America *Ad Hoc* Weather Working Group (1966) that planned increase of rainfall on the East African plains would prevent the periodic droughts which now seem to hold the herds of wild ungulates in check and prevent them from completely overrunning their habitat. Neither is weather modification elsewhere likely to alleviate the most severe and damaging droughts. If, however, downwind decrease in precipitation is shown to occur as a result of cloud seeding elsewhere, the ecological effects are likely to be greatest in dry years.

Form and Intensity of Rainfall

Modification of the drop-size spectrum is an important aspect of cloud seeding, and rainfall intensities are closely associated with drop size. Changes in rainfall intensity may affect erosion processes, plant growth, and animal behavior.

Leopold (1951) has suggested that accelerated erosion in New Mexico during the past 75 years was triggered by a change in the character of rainfall. His analysis indicated that the total amount of rain changed little in this period, but that it arrived in fewer but larger storms, each with greater erosion potential. A substantial fraction of these high intensity storms runs off instead of entering the soil to nourish soil-holding vegetation. Surficial material is therefore more liable to water transport. This mechanism has been invoked by Miller and Wendorf (1958) to account for alternating deposition and erosion of sediment in the Santa Fe region during the period of prehistoric Indian occupation. They suggest that climatic fluctuations consisting only of variations in the ratio of small rains to large, without material change in total precipitation, adequately explain the prehistoric episodes of erosion and deposition. Most authorities consider livestock grazing to have been chiefly responsible for the most recent episode of accelerated erosion in the Southwest; nevertheless, consideration needs to be given to possible ecological effects of changes in rainfall intensity brought about by weather modification. Increasing precipitation from warm clouds might increase rainfall intensity and drop size, and thus increase erosion. On the other hand, seeding of cold clouds with AgI, by initiating condensation at an earlier time, might shift the drop-size spectrum downward and reduce rainfall intensity while increasing the total fall. This would undoubtedly result in lessened overland flow and in more water entering the soil. Marlatt (1967) quotes a rancher in northern New Mexico as saying that the years of a cloud-seeding experiment in the area were the only years in memory that drinking water had to be hauled for livestock. The rancher described the rains of those years as "grass rains" -- gentle, with small drops, and little or no surface runoff.

Other Erosion Processes

Sediment yield from drainage basins is at a maximum in those parts of the United States having 10 to 14 inches of effective mean annual precipitation, decreasing sharply on both sides of this maximum (Langbein and Schumm 1958). Effective annual precipitation in this context is defined in relation to a reference mean annual temperature of 50° F.

Sediment yield decreases as effective precipitation drops below 10 to 14 inches because there is too little runoff to move loosened surficial material any great distance. Sediment yield likewise decreases as effective precipitation exceeds the critical 10- to 14-inch level because increased density of vegetation, supported by higher precipitation, is better able to hold the soil in place. Therefore, an increase in annual rainfall in the 0- to 12-inch precipitation zone would apparently be followed by an increase in erosion. Between about 12 and 45 inches of effective precipitation, erosion should decrease with increased precipitation after a sufficient time to permit increase of vegetation in response to the increase in rainfall. Above about 45 inches, indications are that sediment yield will increase slightly as precipitation is increased.

Stream channel characteristics will also be altered if precipitation is changed appreciably. Channel characteristics are strongly affected by total discharge and by the ratio of sediment load to discharge, both of which are in turn affected by quantity of precipitation. The concentration of sediment per unit of runoff, as a general rule, decreases as runoff increases. On the low side of the critical 10- to 14 - inch level, artificial increase of precipitation will result in somewhat more total runoff, but the sediment concentration in the runoff will not be greatly altered, because total erosion will increase at about the same rate as runoff. On the high side of the critical point, sediment load per unit of runoff will probably decrease as a result of artificial increase of precipitation, at least after an initial period of adjustment, because total sediment yield is expected to decrease at the same time that runoff in increasing.

A river or stream adjusts to new flow and sediment conditions by changing its slope, its cross section, the roughness of its bed, or the sinuosity of its channel. The hydrodynamics of a river results in a channel form adjusted to the discharge and load supplied to it. A decrease in load with constant discharge, or an increase in discharge with constant load, almost always leads to stream aggradation, and vice versa. A river is always either eroding or depositing, but over a period of time long enough to include all the transient fluctuations of discharge and load, a graded stream will display a stable channel (Morisawa 1968). Except in the driest climates, artificial precipitation augmentation is likely to increase stream discharge and velocity more than sediment load. This may lead to channel degradation, and to transport into reservoirs of sediment previously lodged along the banks of the channel. This is most probable in the lower reaches of graded streams flowing through geologically unstable material. Possible responses of steeper headwater sections, which often flow across more resistant material, are discussed later in connection with the biology of lakes and streams.

WETLANDS

Within those regions which receive less than 20 inches of annual rainfall, there are considerable acreages of wetlands important as waterfowl habitat. In addition to the peripheries of water supply reservoirs whose levels are regulated by scheduled releases, there are many smaller stock impoundments, marshes and prairie potholes that support breeding populations of water-dependent birds and mammals. Water levels are largely responsive to local weather. They are a function of moisture conditions of the previous fall and winter as well as of the current year.

Wetlands west of the Rockies produce upwards of one million ducks annually. These ducks and their parent stock comprise about 5 percent of the total fall flight to the Pacific Flyway. Far more important are the prairie potholes, the most productive duck factories per unit area on the continent. The pothole region, only 10 percent of the total North American waterfowl breeding area, produces about 50 percent of the continent's duck harvest. Covering 300,000 square miles in south-central Canada and north-central United States, it includes parts of Alberta, Saskatchewan, Manitoba, Montana, the Dakotas, and westernmost Minnesota (Linduska 1964).

Successful waterfowl production in this region is dependent upon seasonal build-up and recession of water levels on flood plains of rivers and impoundments and in potholes. Waterfowl food production and organic decomposition are both dependent on these cyclic fluctuations. If pothole water levels remained constant, the unique blend of floating, submergent and emergent vegetation required for cover and food would be replaced by less desirable plant communities. If much of the pothole bottoms which are covered by water at high level times were not later exposed to air, oxidation necessary to nutrient cycling would cease or be drastically reduced. Organic debris would accumulate and aquatic succession would accelerate. With minerals and other nutrients locked up in such debris, the pothole ecosystem would be less productive.

Waterfowl production is susceptible to precipitation patterns in other ways. Adequate water levels during the spring nesting season are almost always dependent on heavy and general rains in the fall of the preceding year. Fall wetting of the soil ensures an adequate frost seal in winter. Snowmelt in the spring, running off over frozen ground, effectively fills the marshes and potholes. Spring inflow into the potholes is, of course, a function of winter snowpack as well as of soil preconditioning by fall rains.

Heavy snow, rain or hail in April or May can lead to destruction of nests from flooding or from desertion by nesting hens. This will mean lower duck production. If first nests are unsuccessful, almost all hens will renest, but second attempts are never as successful. If a year's production is unusually dependent on second nesting, adequate water levels in potholes take on added importance. Most potholes begin to dry up in June or July, with the result that nesting habitat is decreased and predation increased.

VEGETATION OF ARID ZONES

Deliberate precipitation increase is not likely to be widely attempted, at least in the early stages of a program, in truly arid regions (less than about 12 inches annual rainfall). The payoff in added streamflow and water storage would be small, and economic gains from vegetation improvement are unlikely to justify the cost.

Yearly herbage production on livestock winter range in the cold desert of Utah, for instance, is markedly influenced by both annual and seasonal fluctuations in precipitation, but average yields are so low that the amount of additional forage produced will seldom be worth the cost of cloud seeding. The estimating equation developed for the Desert Experimental Range in Utah (Hutchings and Stewart 1953) indicates that total air-dry herbage yield would be increased by about 56 pounds per acre as a result of a 20% increase in annual precipitation. This would be a 26% increase in herbage production -- the gain in forage would be more than proportional to the precipitation increase. Nevertheless, the added growth (only 34 pounds of which would be usable under the utilization standards proposed by Hutchings and Stewart) would be worth only about 25 cents per acre to the national economy, based on the grazing values determined by Luscher (1967).

Measurements made in arid regions throughout the world, especially in Africa, have led Walter (1964) to conclude that the average standing crop of vegetation over long periods is linearly related to mean annual precipitation. A long term increase in precipitation would therefore presumably increase the quantity of vegetation on the site.

The percentage increase in vegetation would probably be less than the percentage increase in precipitation, however. This is borne out by observations in the desert north of Phoenix, Arizona (Klikoff 1967). The vegetation in this region forms a continuum from open, widely dispersed small shrubs at the lower elevations to relatively dense tall shrubs at higher elevations. This vegetation continuum is correlated with moisture stress. Where the moisture regime is such that moisture stress is low, larger shrubs such as ironwood and palo verde survive. Under more rigorous moisture conditions, mesquite survives. In yet more rigorous situations, only such shrubs as creosote bush and bur-sage persist. Mean annual precipitation, however, varies by a factor of almost two along this gradient, and associated with increase in precipitation is a concomitant decrease in average temperature due to elevation. Moisture stress is thus quite considerably reduced along the gradient. A 10%

to 20% change in average annual rainfall at any point on this gradient, without a corresponding change in temperature, would presumably result in only a relatively slight shift in vegetation composition toward the higher end of the gradient.

Continuing deterioration of a community of long-lived organisms out of phase with an environment becoming progressively drier may be arrested by artificial increase of precipitation. There is no clear evidence for such a situation in the United States. Some have contended that the impressive saguaro cactus *(Carnegiea gigantea)* stands in Saguaro National Monument and elsewhere in the Southwest are deteriorating and failing to reproduce chiefly because they are relics of an earlier, moister climate, and hence that artificial increase of precipitation should reverse the deterioration. However, Niering, Whittaker, and Lowe (1963) have shown that the species is well adapted to a dry and variable climate. They attribute the reproduction failure to grazing by livestock and rodents and to the interaction of grazing with soil properties. Their evidence does not suggest a probable favorable response of saguaro stands to increased moisture alone. Nor is there clear evidence at present of other important situations of natural climatic dessication in North America upon which artificial precipitation increase could be superimposed as a stabilizing influence.

SNOW MODIFICATION AT HIGH ELEVATIONS

Snow Depth and Vegetation

Vegetation in mountainous areas is usually quite different in areas of deep snow accumulation and in the surrounding area of average snow depth. At intermediate elevations in the Rocky Mountains, woody vegetation is often more luxuriant in and just below zones of drifted snow than in adjacent areas where snow doesn't accumulate, because melting snow recharges soil moisture sufficiently that maximum plant growth can be maintained well into the summer. Higher up, snow banks often persist so late into the growing season that woody species cannot survive and reproduce. The result is a mosaic of grass or heath meadows, representing snow patches, within a forest matrix.

Increasing the mean depth of snow at high elevations therefore may alter the pattern of vegetation in relation to topography. The progressive invasion of alpine fir *(Abies lasiocarpa)* and associated timberline species into heath meadows in the Coast Range of British Columbia has been attributed to lessened snow cover within historic time (Brink 1959). Recession of local glaciers over the past century attests to the reduction in snow.

The length of time that snow remains on the ground is dependent on such weather factors as cloudiness, air temperature, and atmospheric humidity during the melt period, but on the average, the deeper the winter snow accumulation, the longer it will last. Snow in the section of British Columbia studied by Brink doesn't leave the meadows until well into the summer, so snow-free time gained in July and August allows trees to grow where a shorter growing season formerly excluded them. A contrary process would presumably take place if snow accumulation were increased. Deeper snow, lying on the ground longer into the summer, would inhibit growth of existing trees and largely prevent establishment of new ones. This effect is not likely to be as extensive at mid-latitudes as in regions farther north, however. Melting of late-season snowbanks in alpine regions results in steep environmental gradients over relatively small distances. These environmental gradients produce similarly steep gradients in vegetation composition around the snow bank (Billings and Bliss 1959). Unpublished measurements in a typical intermediate elevation mountain region in southwestern Idaho indicate that about half of the winter snow is accumulated on 20% of the area. Late-season snowbanks are confined to an even smaller fraction of the area. Enlargement of these drifts would directly influence the vegetation only in their immediate vicinity.

Snow and Big Game Animals

Big game animals, particularly deer and elk, are economically and esthetically important in much of the U. S. Other less abundant large mammals -- bighorn sheep, mountain goat, pronghorn antelope, and others -- are highly esteemed by an important segment of the public. Many of these animals are critically dependent on winter range which is partially covered by snow during some of the year. The winter range problem is particularly acute throughout most of the Rocky Mountains. This is just the region likely to be most affected by a weather modification program designed to augment runoff into water supply reservoirs fed from winter snows in the high country.

Although the snow management program contemplated by the Bureau of Reclamation and other water supply agencies is initially to be directed mostly toward high mountain zones of deep snow not used by big game during the winter, spillover to lower elevation is not impossible. The effect on wildlife populations might be significant. Perhaps more important from the standpoint of the operating agencies, the public may believe in such an effect even if it does not exist. Wildlife is a subject with such high emotional content that strong efforts should be made to ensure that animal populations are not adversely affected by weather modification, and that the public is aware of this.

In the days before white settlement, deer and elk regularly moved from summer to winter range in the fall and back again in the spring. The vegetation of the high country, attractive in summertime, was unusable under the deep snows of winter, and suitable lowland forage was within easy reach. All available evidence points to snow, rather than to temperature or other weather factors, as the chief cause of the annual migration (Murie 1951).

The migratory pattern persists today, but agricultural and other developments in the lowlands have reduced the amount of winter range in most of the West. Surveys have almost universally shown that wildlife summer ranges in western U. S. are more extensive than winter ranges and provide better forage. The extent and availability of high quality wintering areas largely govern the number of big game animals that can be maintained in healthy and vigorous condition.

Construction of Hungry Horse Dam, Montana, flooded much of the winter range formerly used by the Flathead River elk herd. The elk population is now apparently limited to a size that can be supported by the relatively small amount of winter range where the snow remains shallow enough to permit the animals to move around and to graze without too much difficulty. Local residents are concerned about the effects on the elk herd of the Bureau of Reclamation and Bonneville Power Administration's experimental program to increase snow accumulation above the dam. Even if added precipitation should improve the condition of the summer range, this is already adequate. A 10% increase in snowfall might reduce the already short winter range even further, with effects on the elk herd out of proportion to the actual area involved. This elk herd is highly important to the local economy.

Where winter range is not so constricted, the effect of additional snow on the survival of big game is likely to be directly related to range condition. During the severe winter of 1948-49, deer mortality on overgrazed and depleted ranges in Utah was several times the loss on similar ranges in good condition (Robinette et al 1952). As snow depth increased, much of the already scant browse on the depleted ranges became unavailable. Deer on those ranges had entered the winter in poorer condition than those on better areas, and many were unable to survive the food shortage accompanying deep snow. Winter mortality in this region does not differ greatly between good and poor ranges during years of normal snowfall. Neither is death loss substantially greater in severe winters than in normal winters where the winter range is in good condition. These observations suggest that a precipitation management program aimed at increasing winter snowpacks should be coupled with efforts to improve the quality of wildlife range.

Among the few direct observational studies of big game behavior on winter range is Loveless's (1967) study of deer on the east slope of the Rockies in north central Colorado. The area, between 6000 and 8500 feet in elevation, is occupied between October and April in most years. Snow excludes deer from an appreciable part of the area at various times during the winter. Within the usable portion, the animals move from habitat to habitat seeking the most comfortable temperatures.

The locations used by deer generally had the least snow. Deer or their signs were seldom observed where depths reached 1 to 1 1/2 feet. Snow depths of 10 to 12 inches seemingly impeded movements of deer, especially yearlings. Depths of 20 to 24 inches effectively precluded the animals' use of the area. This depth limitation is confirmed by other references listed by Loveless.

The deer vacated an open timbered ridge on the study area earlier in 1962 than in 1961. The earlier departure in 1962 was clearly a response to deeper and more widespread snow drifts in that year. Snow regularly covered otherwise available food. Only on a few occasions were deer seen to paw through snow to expose covered foliage.

Some large mammals dig for forage more regularly than deer, but they too are limited by snow depth. Caribou in northwestern Alaska failed to dig through more than about 28 inches of snow (Henshaw 1968). Caribou do not inhabit regions that will soon be subjected to weather modification, but their behavior may have analogies to elk behavior, since both are primarily grazers rather than browsers like deer. Caribou conserve energy by occupying wind-shadowed locations during storms and by changing territories and feeding intensively during calm periods. Their feeding behavior suggests that numbers of caribou may be controlled primarily by the morphology of the winter snow cover. Although there are numerous studies of elk winter range condition, there have apparently been fewer direct observations of elk feeding behavior in relation to snow depth.

Like other animals, elk will respond to increases in snowpack differently, depending upon local conditions. A letter from Dr. Richard R. Knight of the University of Idaho describes two instances in Montana where an increase in snowpack may have different effects:

"The Sun River herd in west central Montana summers along the Continental Divide and migrates to the foothills on the east slope during the wintertime. Most of the critical winter range is encompassed by a 20,000 acre game range owned by the Montana Fish and Game Department and in good condition. Strong downslope winds commonly ranging up to 50 miles an hour remove much of the snow from this winter range. During six winters experience on this game range, I remember only one incident where a general snow cover lasts more than 3 days. Dr. Harold Picton of Montana State University and myself have investigated the effects of snow and temperature on migratory behavior of the elk in this area. We have considered snow as a multiplier of cold temperature effects on the elk. We feel that there is a definite more or less straight line relationship between the number of elk migrating down to the winter range and the amount of snowpack and cold temperatures in the mountains. Effects of increased snowpack in this area would probably only force a greater proportion of the herd to migrate to the state owned game range during the wintertime without much ill effect."

"Another example, the Gallatin elk herd, migrates north from Yellowstone Park down the Gallatin river canyon during the wintertime. After many decades of overuse there is very little grass left in the area and this herd subsists mainly on browse throughout the winter. It is probable that the original migration route of this herd to the foothills around Bozeman, Montana has been cut off through settlement of the area. Consequently, this herd experiences critical winter conditions almost every winter. Their browse supply is in poor condition and the canyon winter range normally receives fairly heavy snow cover. Any increase in snowpack on the Gallatin winter range would have serious effects for the elk herd. The north Yellowstone herd to the east of the Gallatin is similarly trapped by civilization into wintering in a high mountain basin. An increased snowpack would quite probably lead to decreased carrying capacity for this herd also."

These comments illustrate the need to evaluate local topographic and forage conditions in any area chosen for weather modification, rather than relying on broad generalizations. The effects of a given additional quantity of snow on wildlife populations are likely to be appreciably differenton the west and the east slopes of most mountain ranges, because of the vegetation contrasts between the generally moister west slopes and the rain-shadowed east slopes.

Large mammals other than deer and elk may in special circumstances suffer as a consequence of extensive artificial increase of winter snow. For instance, the total stock of Sierra Nevada bighorns now consists of some 400 animals in two herds in Inyo County, California. The sheep winter on the steep scarp which forms the east slope of the Sierra. The lower edge of the winter range is marked by the abrupt change in slope where the scarp gives way to the alluvial plain on the west side of Owens Valley. The plain and alluvial fans are used heavily by deer and tule elk; apparently lack of suitable bighorn feed and the presence of competing animal species confine the sheep to the steep slopes. The upper limit of the winter range is set by the fluctuating margin of persistent snow cover. In a normal winter, the upper and lower limits are separated by 2000 to 2500 feet of altitude. The winter range is in satisfactory condition, and the low utilization of key species argues against direct population limitation by starvation. A precipitation increase sufficient to lower the level of continuous snow cover by 1000 feet or more could have serious consequences for this museum-type herd, however, by making winter forage unavailable. The animals are unlikely to move out onto the more level ranges occupied by deer and elk; instead they tend during moderate snows to congregate in canyons where steep slopes and persistent winds prevent deep accumulation (McCullough and Schneegas 1966). It is doubtful that weather modification in this area would actually increase snow depth enough to bother the bighorns seriously, but the possibility should be examined carefully before an operational program is attempted.

In all that has been said so far, it is assumed that weather modification will appreciably increase snow depth on wildlife winter ranges, whereas planned programs are specifically aimed at higher elevation zones normally abandoned by game animals during winter. Nevertheless, it is doubtful that cloud modification can be precisely enough controlled to limit additional snow to lower elevations. Indeed, additional snow might be desired by farmers and ranchers who depend on carryover winter moisture for crop and forage growth. Livestoc on many foothill ranches graze wildlife winter ranges in summer, directly competing (though at different seasons) with game animals. Additional snow which both impeded wildlife use in winter and stimulated growth of livestock forage in spring might be seen as a benefit by ranchers, but not by wildlife interests.

In any case, increased snow cover will not be spread uniformly over the landscape. If the existing mean snow depth during March is say 1 foot (marginal for deer), increasing it to 1.5 feet will not make the whole area uninhabitable. Instead, snow depth will be appreciably increased on some parts of the area and not at all elsewhere. The result will be a reduction in the fraction of the area usable by deer. Depletion of forage in this fraction could weaken the animals to the point that they are more subject to mortality from severe storms, particularly late in the winter.

Not enough is yet known about the pattern of snow distribution as affected by topography, wind, season, and total fall to estimate the extent of the reduction in area usable by deer. Additional research is needed, not only to determine the effect of additional snow on usable winter range but to better define the hydrologic effect of supplemental snow in the high country and at lower elevations. In particular, not enough is known about how snow density, crust formation, and other aspects of snow morphology influence animal behavior and welfare.

Higher elevation spring and summer ranges, particularly those heavily used by elk or bighorn sheep, may also be adversely affected by increased snow accumulation. Croft and Ellison (1960) have vividly shown the damage done to vegetation and to watershed values by excessive numbers of elk feeding on the tender shoots at the margins of retreating snowbanks. The animals' feet churn the wet soil, killing plant roots and contributing to accelerated erosion. Later in the season, after the snow has melted and the surface soil has dried, the snowbank areas provide good forage fed by stored moisture, provided the snow doesn't last so long as to prevent plant growth. The more snow, however, and the longer the snowbanks persist, the longer the animals must depend on the tender and easily damaged vegetation at the snowbank margins. Bighorns behave in essentially the same way, and spring and early summer nutrition is particularly critical to health and reproductive success in these animals (Smith 1958). Here again, more needs to be known about the effect of a given quantity of snow on the size and persistence of snowbanks, as a basis for evaluating both the hydrologic effect of the increased snow and its effect on the health of elk and bighorns.

Where snow burial of winter or spring forage is not crucial, wildlife populations are likely to be aided on balance by weather modification to the extent that added moisture accelerates growth of food plants. Increased moisture is of course likely to improve range condition of critical winter ranges also, but not enough to compensate for the disadvantageous effects of deeper snow. Critically short winter range is likely to be in poor condition to begin with because of past overuse. Its capacity to respond to improved moisture is therefore limited, and if increased snow forces animals to concentrate on a smaller fraction of the area, the net effect is almost certain to be detrimental. Likewise, improved growth of summer forage will seldom be helpful under these conditions, because it will not previously have been in short supply.

Snow and Small Mammals

Even though there have been excellent field studies of the behavior and ecology of small mammals, and of some of the factors regulating population numbers in confinement, there have been few adequate investigations of population regulation in relation to environmental variables in natural populations. It is thus difficult to predict how a given small mammal species in a particular locality will respond to a programmed change in weather, and particularly to a change in snow. Generalizations are almost impossible at this time.

Animals such as the Uinta ground squirrel commonly hibernate for as long as eight months of the year. Since they are underground during practically all of the snow season, it might be assumed that they would be little affected by moderate changes in amount of snow. However, investigations in progress at Utah State University have suggested that the relation of snow disappearance to emergence from hibernation is important in dispersal of juvenile ground squirrels, and hence in the eventual structure of the population. If snow disappears early, older males emerging first from hibernation can establish territories before most of the juveniles emerge. If spring weather is severe, all age classes and both sexes emerge at about the same time, and a clearly different social structure develops. The precise effect of these relations on long term populations is currently being investigated (D. F. Balph, personal communication).

IV. PRECIPITATION MODIFICATION IN HUMID CLIMATES

Heavy demands for municipal, recreational, and industrial water, for hydropower, and for transport of liquid wastes have generated pressures for increasing the supply of usable water in the densely populated humid sections of North America. As in the semiarid West, initial weather modification efforts will be aimed primarily at filling reservoirs. Agricultural and recreational considerations may also be significant.

Humid climates, almost by definition, are those in which precipitation is not the major limiting factor for plant and animal populations or for agricultural productivity. Hence weather modification aimed at increasing precipitation is likely to have somewhat different, and perhaps less marked, effects than in semiarid areas. This is not to say that a change in the precipitation regime of a humid region will not lead to significant alterations in plant and animal communities. The adjustment to new conditions is likely to take somewhat longer than in semiarid areas, however, and perhaps to be partially masked by other concurrent human activities.

It is even more difficult than in semiarid regions to make useful extrapolations from the ecological literature. For example, an analysis of the relation between corn yields and rainfall in the Middle Atlantic states shows that high rainfall in May is associated with depressed corn yields, but from mid-June to late August, above-normal rain is increasingly beneficial to the corn crop. The regression relation developed in this study indicates that an extra inch of rainfall in August is associated with a 22% increase in harvested corn. After the end of August, the effect of additional rain falls off rapidly (Marlatt 1967).

This analysis is highly suggestive, but its results cannot be extrapolated directly to state that an additional inch of rain produced by weather modification in May will depress corn yields, while in August it will increase yield by 22%. For one thing, the analysis necessarily suffers from the fault of practically all such correlations between natural rainfall and agricultural yield or other plant response: temperature is confounded with precipitation. The depressing effect of additional May rainfall is probably due more to the cold temperatures associated with rainy springs in the mid-Atlantic region than to a real excess of water. It might be concluded that an extra inch of artificially induced rain in May is unlikely to reduce corn yield much if temperature remains unchanged, but neither is yield likely to be increased. On the other hand, it is not illogical to assume that an inch of artificial precipitation in August could well augment corn yield an average of 22% as suggested by the regression equation. Similar difficulties of interpretation are associated with practically all studies of plant and animal responses to weather and climate in humid temperate regions.

THE CONNECTICUT RIVER BASIN AS EXAMPLE

The Connecticut River Basin is relatively typical of other river systems in the industrialized eastern United States. The U. S. Bureau of Reclamation has negotiated a contract with Travelers Research Corporation to analyze the meteorological feasibility and economic desirability of weather modification in the Connecticut Valley (Aubert et al 1968). Results of this study are expected to be used as a guide to planning and policy in other similar basins. The existence of this concurrent study suggested using the Connecticut Valley as a prototype area for a preliminary survey of possible ecological effects of weather modification, based on a review of the available literature and on interviews with individuals in universities, forest and agricultural experiment stations, state game, fish, and forestry departments, and other organizations.

Probable Weather Modification Operations

Water supply (municipal, industrial and private), flood control, hydropower, waste disposal and recreation are the water uses in the Connecticut River Basin of major present and future importance. Irrigation and navigation are not nearly so significant. The main municipal water supplies for Hartford, Connecticut, and Springfield and Boston, Massachusetts, as well as those of lesser communities are all within the Connecticut River Basin. The storage capacity of present and projected dams is adequate to retain normal runoff, though spills do occur in spring when streamflow is increased by melting of snow.

The Connecticut River and its tributaries reach their minimum flow during the summer. Demands for water for industrial, municipal and private consumption, waste disposal, cooling, and hydropower normally increase during this period despite the reduced ability of the resource to meet the demands. In addition, demands for water for swimming, boating, and fishing are highest in the summer when water supplies are lowest and water quality least satisfactory. Consequently, the most beneficial weather modification operations are likely to be those which increase summer streamflow (Aubert et al 1968). Augmented snowmelt runoff would largely be wasted at present because of insufficient storage capacity. There are rather firm plans for additional dam and reservoir construction, however. Additional snowfall might in the future be desired to help fill the increased storage capacity.

It is also conceivable that resort operators would favor efforts to increase snow pack during the skiing season. There may also be some limited and localized attempts at precipitation increase for agricultural purposes, mostly during spring and summer.

Ecological Impact on Aquatic Communities

The Connecticut River supports aquatic communities of varying degrees of economic importance. Shellfish in the estuary, a shad industry in the lower reaches, and an anadromous fish (Atlantic salmon) re-introduction program in the Connecticut and Massachusetts portions of the river are of prime importance. In addition, of course, is the extensive sport fishing which the river and many of its tributaries provide each year.

Because the flow of the river and its tributaries is largely regulated by reservoirs and control structures, additional water production in the watershed would be unlikely to have a detrimental effect on these aquatic communities. Native aquatic communities might in fact be favored if more stored water were available for release during low flow periods, when chemical and thermal pollution are most serious.

Biologists responsible for management of fisheries or other aquatic resources, when interviewed in the course of this investigation, could conceive of few situations where precipitation management might prove inimical to their interests. In the case of fish stocking programs near state lines, fish planted in one state might be swept downstream to benefit another state's anglers if water flows increased from a heavy storm on days of stocking or immediately thereafter. Such a hypothetical problem, however, could be avoided by communication between appropriate officials prior to any planned weather modification operations.

Ecological Impact on Terrestrial Communities

If successful precipitation modification in the Connecticut Valley is confined to the summer season, its ecological effects will be related principally to partial alleviation of mid-summer moisture deficiencies. Some acceleration of tree growth in forest plantations and natural forest stands, and minor changes in non-forest vegetation, might be anticipated.

Temperate forest trees respond differently to moisture stress and its alleviation at different stages in their annual growth cycle. Daily water deficits result in physiological conditions which largely determine how much new tissue can be formed and when during the growing season it is laid down (Fritts, Smith and Stokes 1965). Water stresses are not serious in most tree species before midsummer, by which time absorption by roots normally lags behind transpiration. Dehydration of tissues in the crowns and stems then causes growth to fall well below the potential for that time of year. If the mid-season water deficit has not been too severe, radial growth of most trees responds immediately to soil moisture recharge at any time during the growing season (Phipps 1961; Zahner and Donnelly 1967). Extended rainy periods during flowering may decrease pollen dispersal, but additional rain a little later could lead to production of seed with greater than normal food reserves and embryo vigor (Zahner 1968).

Wood quality is becoming as important an objective of forest management as total growth. Wood quality is closely associated with the amount of latewood produced each year. Favorable water relations late in the growing season apparently contribute to increased width of the latewood band in several species of pines. Alleviation of moisture stress by midsummer irrigation over a 7-year period resulted in production of up to 40% more latewood by 100-year-old ponderosa pine trees in eastern Washington than in similar trees not watered (Howe 1968). However, latewood production in other species of Pinus is not affected by summer water deficits. It is apparently an intrinsic character of eastern white pine *(Pinus strobus)*, an important commercial tree in New England, to produce only 6-8 latewood cells per radial file each year regardless of weather. It therefore appears that wood quality in some, but not all, conifers would be improved by additional midsummer rain (Zahner 1968).

Non-woody plants of pasture and woodlot would presumably also be affected primarily through alleviation of summer water deficits, as would many agricultural crops. Most annual crop plants are especially sensitive to water stress from the time of flower bud initiation through the flowering period, and to a lesser extent during early fruit development (Salter and Goode 1967). An early stress has an indirect effect on final yield of grain by reducing the size of the assimilating surface that will ultimately be available for photosynthesis, since stress applied during active expansion retards enlargement of plant parts. Recovery after the stress is removed is not immediate, but growth rate appears to return to normal after a few days. Later stress has a more direct effect on grain yield by reducing assimilation in the critical period when photosynthesis is high and most assimilate is going into grain (Denmead and Shaw 1960). The precise effect of augmented precipitation would therefore depend in part on when during the plant's life cycle it is applied.

It should be pointed out again that weather modification is unlikely to do much to alleviate the severe droughts that are the most damaging to vegetation. A successful weather modification program could, however, somewhat increase mean annual growth of forest stands and increase the luxuriance of understory vegetation. It is doubtful that there would be major changes in seedling establishment or stand composition, particularly since much of the non-cultivated land in this densely populated region is regularly treated by its owners to deliberately alter its species composition. Changes that do occur will mostly be slow, and will be evident only over a considerable time span.

Modification of Snow Pack

As already indicated, economic benefits visualized from weather modification in the Connecticut Basin are primarily associated with increased summer rain. If a program to augment winter snow were deemed feasible and desirable, however, it could have consequences for plant pests and wildlife populations.

Forest entomologists and plant pathologists who were consulted in the valley were agreed that any population changes likely to result from the kinds of weather modification postulated would be manageable with current control practices. One effect likely to be of specific concern in the Connecticut Valley, however, is that of the timing of a lasting snow cover. If a sufficient insulating snow blanket is established prior to frost penetration, many overwintering insects such as balsam wooly aphid and pathogens such as white pine blister rust will be favored. Timing of snow cover establishment is likewise of interest to growers of red spruce Christmas tree plantations, as this species is particularly sensitive to frost injury when not covered by snow.

Snowfalls during deer hunting seasons, particularly just before a weekend, markedly influence hunter success and deer harvest by making tracking easier and by muffling hunters' movements. In years in which deer are heavily concentrated and wintering poorly, increased snowfall could lead to heavy starvation of weakened deer. In a small state like New Hampshire where non-resident and resident hunting provides a significant yearly income, anything which adversely affects the state's deer resource could have immediate and potent political consequences. Deer yarding problems need to be regularly considered in Vermont and New Hampshire, less often in Massachusetts and Connecticut.

Ecological Benchmarks

The Connecticut River Basin has two prime benchmark studies against which to check for future vegetative changes brought about by either natural or man-made climatic shifts. One of these is a series of four mixed hardwood stands maintained by the Connecticut Agricultural Research Station on which every tree has been individually noted and measured periodically for more than 40 years. These stands provide an unusually precise record of species changes over the past four decades; future changes can thus be better interpreted.

Another such study is one carried out over the past several years which consisted of mapping the range of all species of oaks throughout New England on U.S.G.S. topographic maps. These sheets of 1 inch to the mile scale will be permanently filed at the Harvard Forest, Petersham, Massachusetts. Future changes in the region's climate may be detected at the margins of the ranges of oak species, as these margins would shift with modified climates. If weather modification operations were to lead to such a changed climate, this benchmark study may permit its detection.

OTHER HUMID TEMPERATE REGIONS

The Connecticut Basin has been considered here as a prototype of similar areas in the densely populated eastern United States. There will be local differences, but it is believed that the general conclusions from the Connecticut Valley can be extrapolated fairly widely.

Data on pests and diseases, and on the potential effects of modifying the large tropical storms that influence the precipitation pattern of eastern North America, are discussed elsewhere in this report. There are also a few other potential ecological effects of weather modification in humid regions that deserve consideration.

Wetlands

Bogs, swamps, and salt marshes could have their water supply increased through weather modification, and water tables in adjacent areas might be brought nearer the surface. This could be disadvantageous in commercial forest stands where inadequate ground water drainage and high water table conditions restrict tree growth. This is notably the case in spruce stands in the Lake States, and in swamp hardwoods and poorly drained pine sites in the Southeast.

Higher water levels could benefit wildlife populations dependent upon a shrinking acreage of wetlands, particularly salt marshes. These environments, exceedingly valuable as spawning grounds for marine organisms, are often highly dependent upon periodic inflows of fresh water. Detailed surveys of the biological and hydrologic situation of wetlands should be made in each specific area where weather modification is proposed.

One area where deliberate increase of precipitation has been seriously proposed chiefly for the benefit of natural communities is the Florida Everglades. Land drainage and alteration of natural flood patterns have greatly reduced the normal inflow to Everglades National Park. The unique plant and animal communities of the Everglades, largely dependent upon wetland conditions for their existence, have suffered as a consequence. Artificial precipitation might help this situation. It is almost certain, however, that even the most successful weather modification program cannot by itself maintain the natural values of Everglades National Park. It is important that the prospect of a partial solution to the

Everglades problem some years in the future should not lull the public, or state and federal policy-makers, into a feeling that nothing else need be done.

utrient Loss from Fully and Sparsely Vegetated Ecosystems

The input, internal circulation, and output of dissolved mineral substances in ecosystems is a complex process involving interactions of climate, geology, soils, and vegetation. The long term productive capacity of a site can be lowered by excessive leaching of mineral nutrients. Leaching is likely to be almost proportional to increased rainfall on well vegetated watersheds and accelerated on depleted areas.

Vegetation cover regulates nutrient output both by storing nutrients in living organisms and by influencing the flow of water through the soil profile. Concentrations of Ca, Mg, K, and Na in streamflow from small forested watersheds in central New Hampshire have varied relatively little from year to year, even though the years of observation included a drought period that drastically diminished runoff and a period of above normal precipitation (Likens et al 1967). This suggests that a moderate increase in mean annual precipitation could be expected to increase total output of nutrient elements from forested basins such as these, but probably not the concentration of nutrients in the runoff water.

In regions of lower rainfall, mineral concentrations, and sometimes even total output of minerals, are commonly lower at times of high flow than at low flow. This is due to the long residence time of water in the soil during dry weather, affording more opportunity for chemical reactions. Furthermore, at a given flow rate, concentrations are often lower when a stream is rising than when it is falling. This can be explained by the fact that during periods of stream rise, following rain, most water moves as subsurface flow through the top few centimeters of the soil. Some rain also enters root channels, worm holes, and other crevices, and flows through these openings without coming into real contact with the soil. The energy relations of soil moisture, however, prohibit water from remaining in such openings unless the soil is at or near saturation. Thus when streamflow begins to recede, moisture is confined to small pores, where it comes into intimate contact with chemically reactive sites on soil colloids. Particularly if artificially increased precipitation comes mostly in a relatively few large storms, leaching is not likely to be greatly increased in these circumstances.

Removal or depletion of vegetation may alter the situation, however. Clearcutting of the forested catchments described above dramatically increased the outflow of mineral elements and tended to deplete the system of nutrients (Bormann et al 1968). The accelerated rate of loss is related to cessation of nutrient uptake by plants and to the larger quantity of drainage water passing through the system because of reduced transpiration. Similar effects might be expected if flow of water is artificially increased without enough vegetation to pick up the mobile nutrients, as in unprotected plowed fields or severely overgrazed pastures.

V. PESTS AND DISEASES

A weather modification program that loosed a plague of destructive insects, plant diseases, or noxious weeds would be transformed from an economic boon to a disaster. It is therefore important to ensure so far as possible that planned changes in precipitation or other weather variables do not trigger such outbreaks.

INSECT POPULATIONS

Moderate changes in insect abundance may well occur as a consequence of weather modification. This need not cause concern if there is reasonable assurance that a 10% to 20% change in annual precipitation will result in no more than a proportional change in insect numbers.

A pest is an abnormal, not a normal, biological phenomenon. The vast majority of the 2 million or so species of living organisms are remarkably constant in numbers from year to year. According to Watt (1968), a pest is a species operating without a long-evolved set of regulating relationships with other species in its environment. Some pests seem to be controlled mostly by density-independent processes rather than by feedback mechanisms involving their own numbers. Climate is one of the agents sometimes responsible for fluctuations in pest abundance. It is unlikely, however, that weather modification of the kind now visualized will set off major insect pest outbreaks except under rather special circumstances. In part this is because temperature has a greater influence on the population behavior of the majority of insects than does precipitation, although interactions of precipitation with temperature are also important.

Rainfall frequency is likely to be the most critical variable governing the numerical response of insect populations to minor weather fluctuations. For moisture does not act on insects like temperature; below catastrophic levels, the regularity of precipitation has more impact than the amount. Increasing the amount of local precipitation by 10-20% would seldom produce a conspicuous change in the numbers of resident insects if the precipitation increase were achieved wholly by augmenting the mean rainfall per storm without significantly affecting the number or duration of storms. But increasing the number of storms during the growing season by 10-20%, whether or not the total rainfall was effectively increased, could generate a delayed numerical response.

Insect Outbreaks

Entomologists and others have distinguished between the *spreading-out* and the *scattered* types of pest outbreaks (Watt 1968). In the former, an infestation occurs first at one place and then spreads out gradually from year to year; the total area infested increases from year to year, then rapidly decreases after the peak is passed. In the scattered type, infestations occur simultaneously at many places scattered over a vast area.

Scattered outbreaks are not likely to be triggered by weather modification programs. The discrepancy in the sizes of the two kinds of areas involved -- a few hundred square miles in local weather modification programs, and several thousand square miles in widespread outbreaks -- is simply too great for events in the smaller area to have much influence on processes in the larger.

The situation might be different with pests of the spreading type. The spruce budworm, a major pest of balsam fir forest in Canada and northern United States, sometimes may be in this category. Once a spreading budworm epidemic has developed and gained momentum, its effects generally obliterate environmental differences that might have contributed to its spread, but local weather may be important in triggering an outbreak. Survival of overwintering larvae is promoted by early snow, frequent replenishment of insulating snow on conifer branches, and continuing cold. The larvae emerge in spring. In addition to rising temperature, some rainfall prior to emergence seems to be essential. After emergence, dry and sunny weather with light wind is ideal for establishment of larvae on feeding sites and for their continued growth. There is a good negative correlation between budworm defoliation and June rainfall. Thus there is at least a possibility that local augmentation of June rainfall may be a useful auxiliary measure in spruce budworm control programs. However, such local treatments could trigger an outbreak of another somewhat less destructive insect, the forest tent caterpillar, which thrives in cool, moist summers. There is generally a negative correlation between the abundance of the two organisms where their hosts coexist (Wellington 1954).

Grasshoppers may also be affected by weather modification. Warm, dry, sunny weather favors high survival, rapid development, and maximum egg production of many economically important species. Cool, moist conditions, particularly in spring, increase mortality, delay development and maturation of adults, and reduce egg laying, so that populations tend to decline. Most grasshopper eggs are laid on bare soil partially sheltered by adjacent vegetation. Eggs are less abundant in dense vegetation. A cool showery spring extends the hatching period, reduces concentrations of hatchlings, and retards their tendency to move from the egg grounds into crops and pastures (Pickford 1966).

Statistical analysis of a long record in Saskatchewan has shown a direct relationship between abundance of grasshoppers and mean monthly temperatures from July through September of the preceding three years (Edwards 1960). There is a weaker relationship between grasshopper populations and total precipitation during the April-August period of the preceding two years. The association between grasshopper populations and weather conditions has persisted in spite of vigorous control campaigns in certain years and in the face of continually changing cultural practices. It is not yet possible to say whether the association is brought about by direct action of weather on the insects' physiology, by indirect action on their food plants, or by differential effects on their parasites, predators, or diseases. Furthermore, the statistical procedure used in the investigation was not designed to detect a separate effect of precipitation after control for temperature. Edwards, however, cited several previous investigations which showed that, while most grasshopper outbreaks have followed periods of hot weather, in only about half the instances investigated have outbreaks followed periods of dry weather -- no more, in fact, than might have been due to chance. The direct effect of rainfall on grasshopper populations remains uncertain, but it does not appear from the facts cited above that precipitation increase will bring about an immediate grasshopper outbreak.

There is a possibility that increased food supply owing to several years of artificially increased rainfall might increase grasshopper populations moderately, although not to plague proportions. This might result in more than the normal number of eggs, and it is known that large egg infestations generally produce a grasshopper outbreak if the next spring is warm and dry (Pickford 1966). Weather modification as currently visualized will not eliminate the occasional dry years that are a significant feature of the grassland climate, since these dry years are governed by regional airmasses and the general circulation and not by microphysical precipitation processes within clouds. When dry years do occur it is possible that the grasshopper outbreak will be worse than it otherwise might have been, because of the effect of increased food on previous egg production.

Other insects, beneficial and detrimental, may also be affected in complex ways. For example, in moist years in western Kansas, prickly pear (*Opuntia* spp.) is so heavily infested by insects that it may disappear from some communities. In dry years it tends to increase.

Farms, Gardens, and Towns

On a purely local scale, the chances of inadvertently increasing or decreasing the numbers of different species during a successful program of weather modification are great enough to merit some consideration. At the micro-scale level of suburban home gardens, for example, or even on the slightly larger scale of truck gardening, farming, or nursery operations, real success in sustaining an abnormal frequency of precipitation over a few hundred square miles probably would be accompanied by localized infestations of certain insects, such as mosquitoes or some of the more hygrophilic aphids. If the total ecology of the area demonstrably would benefit from increased precipitation, then specific hazards, including localized infestations, could be evaluated beforehand and minimized by appropriate action. But planning for weather modification programs obviously would be inadequate if it disregarded the possibility of local infestations. And at certain critical points during the growing season, some consideration also would have to be given to the effects of increased precipitation on some of the more xerophilic insects, notably the more important pollinators. In major farming areas, inadvertent interference with the pollination of forage and fruit crops would always be unwelcome, and occasionally disastrous.

Pesticides and Biological Control

Inadequately planned weather modification programs could also indirectly influence local population trends through the action of precipitation on chemical pesticides. Despite some obvious disadvantages of chemical methods of pest control, our own population needs ensure that large-scale control programs will continue to be a significant ecological feature during the foreseeable future. Few insecticides have their action improved by rain-washing immediately after their application. In the interests of efficiency, therefore, it would be only common sense to integrate large-scale applications of chemicals into the appropriate gaps in a weather modification program. But such integration would require better communication between the respective agencies than now exists.

Weather modification by itself is not likely to be a useful tool for controlling insect outbreaks. Insect outbreaks are not like forest fires; they cannot be doused. Manipulating them by directly exploiting their weather sensitivity would require greater ability to control the frequency of precipitation than weather technologists are likely to possess in the foreseeable future.

However, precipitation modification could be a useful adjunct to biological control programs. Some insect pathogens could be rendered much more effective if they could be better synchronized with periods of precipitation. Pathogenic fungi can decimate insect populations in a sufficiently humid habitat, but the problem has always been to obtain the appropriate humidity when it was most required. Since that problem has generally seemed intractable, exploitation of moisture-sensitive diseases has been neglected in natural control programs. Wherever such pathogens could be brought together with the susceptible insects during a program to sustain increased precipitation, however, the chances of inducing an epizootic would be much improved. The possibility of integrating microbial control with weather modification programs therefore should not be overlooked; the prospects should be explored through consultations with insect pathologists. Indeed, it might be possible to design pilot projects to test appropriate pathogens by using existing irrigation sprinkling systems in farm or range environments. Successful cloud-seeding is not really necessary for small-scale tests designed only to explore the possibilities.

There are some special instances where increased rainfall might reduce insect damage. Additional summer rain might reduce bark beetle attacks on some kinds of forest trees. Thus, in Douglas fir, oleoresin exudation pressure is an indicator of the water condition within the tree and hence of its physical condition. A high oleoresin exudation pressure helps the tree to repel bark beetle attacks (Rudinsky 1966). The same is true of ponderosa pine.

Effects of Increased Snow

Artificial increase of snowfall is likely to affect insect populations somewhat differently than increase in rain alone. The amount and duration of snow cover are important in overwintering of many insects, and changing these quantities may alter insect numbers. For example, survival of grasshopper eggs in Saskatchewan is dependent upon the depth and extent of snow cover as well as upon the intensity and duration of subzero temperatures (Riegert 1967). Snow is an excellent insulator, and deep snow protects the eggs from lethal cold.

On the other hand, it has been suggested that the insulating effect of additional snow from a weather modification program might encourage survival of the western pine beetle (*Dendroctonus brevicomis*) and other bark beetles sufficiently to trigger an outbreak. This is unlikely, for the lowest few feet of a tree stem, which retain moisture in bark and sapwood the longest, are the last to be attacked, and they may even be ignored entirely (Miller and Keen 1960). The majority of overwintering beetles are too high in the trunk to be protected by additional snow.

PLANT DISEASES

Weather is important in the spread and intensification of plant diseases; deliberate increase of rainfall or other weather modification, especially during the growing season, will undoubtedly alter patterns of disease occurrence. Plant diseases in which the causal agent is dispersed to above-ground parts of the host will be most strongly affected.

Effects of weather modification are likely to be different on diseases of cultivated annual crop plants and on diseases of perennial trees and shrubs. In grains and other agricultural crops, the important distinction between a severe disease outbreak and a mild one is time. An unusually severe epidemic is one that reaches high levels of disease a week or two earlier than usual in relation to the time when the fields ripen. Early development can arise from early dissemination of inoculum or from a high infection rate during the growing season (van der Plank 1963). Diseases of perennial plants, on the other hand, are most destructive when there is massive or repeated inoculation, so that the pathogen eventually overwhelms the host.

Potato Blight - An Example

Late blight of potato is the plant disease whose epidemiology has been most widely studied (Cox and Large 1960). This is the disease responsible for the tragic nineteenth century Irish potato famine. That outbreak was apparently triggered by several years of weather cooler and wetter than normal -- the conditions sought by some proponents of weather modification. Modern agricultural technology and disease control methods, and greater crop diversification, make any such catastrophe most unlikely today as a result of weather modification. Nevertheless, potato blight is an example of a disease that could be made worse by a shift toward a more humid climate.

The fungus overwinters in infected tubers, and infection results when mucelium invades young stems arising from seed tubers. The fungus fruits on stems and later on leaves under humid conditions. In a few places in the world the disease is endemic, meaning that it occurs to a damaging amount every growing season. Such an area is southwest England. Another is southwestern Ireland.

In many other parts of northwestern Europe, the disease appears in epidemic form some years but not in others. In the British Isles, a great deal of attention has been given to the relation of epidemics to weather. The weather in these areas is generally very favorable to potato growth and development, i.e. high rainfall and mean temperature between 50° and 60° F. The "blight years" are characterized by high rainfall and temperatures slightly above 50°. Thus it is evident that the ideal weather for the potato coincides closely with that of the disease. Records show that yield is always higher in blight years than in non-blight years, but in the former there is much more tuber rot after harvest. Tuber rot is best controlled by destroying the vines before 1% of the foliage has become infected (Hirst et al 1962).

The fungus fruits most profusely at about 55°. When rainfall is below average and temperature higher than a mean of 60°, especially during July and August, blight either does not occur or damage is minor. It is important to point out, however, that sustained humidity is more important than rainfall alone to blight development. Thus if rain is followed by bright skies which bring high temperatures and low humidity the development and spread of the fungus is checked.

The intensive study of blight in relation to weather has been prompted by the need to make blight forecasts. The latter are essential to advise growers if and when sprays should be applied. One of the earliest and most thorough studies has been made in southwest England by A. Beaumont (1947). As a result of many years of study the so-called Beaumont rule is followed in the area and it is used, sometimes with modifications, in other areas. By the Beaumont rule, spells of not less than 48 consecutive hours, during which relative humidity does not fall below 75 percent and the temperature is not less than 50°, are expected to be followed by blight outbreaks within 14 to 21 days.

On the basis of this brief summary one may speculate what result would follow artificial rain in a given area. It is not likely to have much effect in an endemic area but in epidemic areas it might mean a change from a "non-blight" or "light blight" season to a "blight season". Cox and Large have analyzed the rainfall and temperature in July and August, the most critical months, at Cambridge, England, for 5 "blight years" (1948, 1950, 1953, 1954, 1956) and 5 "other years" in the same decade (1947, 1949, 1951, 1952, 1955). In the blight years the average rainfall for July and August was 3.3 and 3.9 inches respectively, while in non-blight years it was 1.3 and 1.9. The mean temperatures for the two months during the blight years were 61° and 60° F. and for the other years, 65° and 64°. It would appear from these data that an increase in blight could have been expected if 2 to 3 inches were applied artificially during the "other years" in July and August. Here as elsewhere, the situation is complicated by the normal association between high precipitation and high temperature, which is not likely to hold under a rainfall augmentation scheme.

It may be more pertinent to consider what would happen where the disease is "spasmodic". This term applies to disease when it appears in severe form only perhaps once in 5 years. One of the most intensive potato growing areas of the U.S. is Aroostook County, Maine. This may be classed as an "epidemic" blight area. By contrast in the Red River Valley of North Dakota and Minnesota the disease is spasmodic. In a ten-year period (1946-1955) blight was important in only one year and it was absent or unimportant in nine. In 1948 blight was prevalent only in the northern part of the valley. This year showed above 4 inches of rain in June, July and August, which in a cool area would surely have resulted in a general epidemic. The mean temperature, however, was between 58° and 70° for these three months. It is quite possible that high temperature is the most important factor keeping blight to a minimum. In western Nebraska potatoes are grown extensively under row irrigation in the vicinity of Scottsbluff. Blight is practically unknown. Low rainfall, low relative humidity, and high temperatures combine to prevent development of the disease.

One might speculate as to the effect of artificial rain on blight in the Red River and Scottsbluff areas. It is not likely that an additional 2 to 3 inches per month during July and August would lead to an epidemic, largely because this would not be likely to incite a long enough period of high relative humidity to start off and maintain the fungus even though it had been introduced in seed tubers. In the Red River Valley which is a relatively high rainfall area, additional development of blight might be enhanced. It is not likely that epidemic proportions would appear because of prevailing high temperature in July and August.

In summary, if weather modification increased rainfall by 2 inches per midsummer month there would in most cases be little detrimental effect on the incidence of late blight. The actual result could only be determined by a long series of years of experimentation in various areas.

Seed-Borne Diseases

Two important diseases of cabbage, black leg and black rot, are seed borne. Before 1920 most cabbage seed was produced in Long Island and in Holland and Denmark, and epidemics were common when this seed was planted in the Midwest. The principal seed growing area today is the Skagit Valley of Washington. This coastal area has rainy and foggy weather during most of the autumn, winter, and spring, but summer is almost rainless. Development of blackleg inoculum in quantities sufficient to initiate an epidemic proceeds only in the presence of summer rain. During the last half century, only one lot of seed produced in the La Conner area of the Skagit Valley has resulted in an epidemic when planted in the humid and semi-humid commercial cabbage areas east of the Mississippi.

This example is one in which absolute prevention is essential. The data indicate that lack of rainfall in July and August is the key point in production of disease free seed. It is indeed a question how long the Skagit Valley would be safe for cabbage seed production if rainfall were increased by artificial means in July and August. Fortunately, summer air mass conditions in this region are such that a successful rainfall augmentation program in summer is unlikely; nevertheless, the point is clear that specialty crop areas require especially careful evaluation to insure that weather modification does not upset the conditions that initially made the area desirable for the purpose.

Another group of foliage diseases where rainfall has played an important part is that including anthracnose and two bacterial blights of bean, and the Mycosphaerella blight and the bacterial blight of pea. Until about 1930 these diseases were commonly epidemic in growing areas east of the Mississippi River. They caused heavy losses in yield and quality of crops produced for canning. All are incited by seed-borne organisms and all are disseminated in one way or another by rain. No satisfactory measure has been devised for disinfecting disease-bearing seed. In the bacterial blights and bean anthracnose the spattering of wind-blown rain is the chief disseminating factor. In the case of Mycosphaerella blight of pea, pycnospores are water-disseminated while the ascospores are discharged from perithecia into the air. While air turbulence is important in this connection rain or dew is essential for discharge of ascospores.

Production of seed of pea and bean was concentrated in Wisconsin and New York until about 1915. As seed production was expanded to irrigation areas in the west it was observed that these diseases declined noticeably on crops in the midwestern and eastern humid area when grown from western seed. The improved seed came mostly from the plateau in the vicinity of Greeley, Colorado, the Big Horn Valley of north central Wyoming and the Snake Valley of lower Idaho.

The decline of these diseases in crops grown from western seed was so marked that seed growing was quite rapidly shifted from Wisconsin and New York to these areas and to a limited extent in the Sacramento Valley of California. After about a decade epidemics of bacterial blights of bean, especially a halo blight, began to appear in eastern growing areas. It became quite evident that since the seed lots used in these cases were produced in the Greeley and Big Horn areas that there was a limited amount of disease infection of seeds in this area. It is significant that in the next decade growing seed of canning varieties of bean and pea was abandoned in these areas and acreage was moved farther west. Generally speaking this practice has resulted in elimination of the bean anthracnose organism and to a large degree that of Mycosphaerella blight. Occasional cases of halo blight of bean and bacterial blight of pea have been traced to infected seed from lower Idaho. While complete elimination of the bacterial pathogens has not always occurred, the diseases have been held to a minimum in Idaho, Washington and California. In fact practically all bean and pea seed used in the United States comes from this area and some European countries are now drawing from the same source because of the disease-free nature of the seed crop. Due to occasional infected pea and bean crops in the Idaho area, seed growers have for the most part avoided use of sprinkler irrigation. This was a major factor in reducing and for the most part excluding halo blight epidemics in crops grown in humid areas from Idaho grown seed.

The data presented on development of seed-borne diseases in favorable and unfavorable areas give some indication of what might happen if artificial rain were used in the areas presently used for seed growing. These examples represent what may be found in the literature which might throw some light on the major question. These examples also show how inadequate the data are to predict what might occur in plant disease development in any given area.

Sprinkler Irrigation Experiments

In the above discussion of bacterial blights of bean it could well be concluded that overhead irrigation as opposed to row irrigation would change the picture markedly. It should if sprinkler irrigation is also accompanied by temperature and relative humidity comparable to that in humid areas (e.g. Wisconsin). In 1950, 1951 and 1952, experiments were conducted by Menzies (1954) at the Irrigation Experiment Station, Prosser, Washington. This is in the Columbia River Basin where natural rainfall is sparse. Row irrigation and sprinkler irrigation were compared as to spread of common bacterial blight on Red Mexican bean, a variety grown extensively for the dry bean crop. In each case a few plants in each plot were inoculated with the pathogen. The disease developed on these plants and gradually they became defoliated as the season progressed. The spread from such inoculated plants to surrounding plants was recorded.

Rather heavy sprinkler irrigation in 1951 and 1952 resulted in little or no spread. A larger number of irrigation applications in 1950 did result in increased inoculation. Nevertheless, disease incidence was much less under heavy sprinkler irrigation than in a humid area as Wisconsin. To quote Menzies, "In comparing sprinkler and natural rain there are several differences, important to the spread of plant diseases, that should be noted. Natural rainstorms usually cover large land areas; they are usually preceded by a period of cloudy weather during which temperature falls and humidity increases. The rain is often accompanied by wind. After the rainfall there is a variable time of high humidity and cloudiness during which temperatures again rise to the normal arid level."

"Artificial sprinkler rain is usually applied suddenly under hot, arid conditions and as abruptly terminated. The small land area involved is surrounded by hot, dry air which immediately moves in over the sprinkled field if there is any wind movement. Free water on crop foliage may be gone within 30 minutes after sprinkling ceases during hot weather, and the temperature drop is of short duration."

"Sprinklers are probably more effective in dissemination of inoculum than is gentle natural rain. This is especially true of high pressure, low angle rotary sprinklers. They compare more to the heavy, beating rainstorms that accompanied wind. Large droplets of water are delivered at a driving angle to the plants and thus splash from plant to plant."

Another case of the effect of sprinkler irrigation versus row irrigation in an arid area has been described by Wilson (1968): "Annual crops grown in California during the summer season, which usually is rainless and low in humidity, are generally free of certain 'wet-weather' diseases so long as irrigation is by furrow or basin methods. When, however, sprinkler irrigation is introduced, such diseases as bean halo blight, bean anthracnose, melon black rot, and cotton angular leaf spot become prevalent. Though cotton leaf spot was undoubtedly introduced many times into California on contaminated cotton seed, the disease became troublesome only where sprinkler irrigation was used. Changes in type of irrigation, use of seed from furrow-irrigated fields, and a few other procedures has practically eliminated the disease from the state. Though modern types of orchard sprinklers throw streams of water to heights of only 5-6 feet, upward currents of air carry the mist much higher, thereby increasing humidity in the upper parts of the trees. Under such conditions the following diseases have been reported to increase in severity: almond hull rot, prune rust, apple perennial canker, apricot shothole, Phytophthora fruit rot of pear, apricot and peach, fireblight of pear, and twig infection of apple by *Podosphaera leucotricha.*"

It should be pointed out that in the study reported above sprinkler irrigation was substituted entirely for furrow irrigation. This would involve 15 inches or more being applied in a growing season. This is substantially more than would be involved in the plans suggested for artificial rain.

Virus Diseases of Plants

Bacterial and fungal diseases of plants, including most of those discussed above, are primarily spread by wind or rain spatter, and are heavily dependent on favorable humidity and temperature for establishment on newly infected hosts. Virus diseases, except for a few like tobacco mosaic virus that are highly infectious and easily transmitted by contact, are almost always distributed by arthropods, usually insects. Aphids and leafhoppers are the principal vectors, and most work has been done on them. The influence of climate and man on virus distribution is known for only a few viruses, because the vectors of many viruses are still unknown. The available information on the influence of climate and weather on plant virus diseases has been summarized by Broadbent (1967).

The seasonal cycles of insect vectors vary with climate, and with weather from year to year. In temperate and moist tropical climates, temperature is the most important regulating factor, whereas rainfall dominates in arid climates. Viruses spread fastest under conditions optimal for insect multiplication and activity. It is often difficult to disentangle the effects of rain from those of temperature. Fewer winged aphids develop during cool, wet weather, and as rain also hinders aphid flight, fewer new colonies are formed than when it is warm and dry. Heavy rain washes many insects off plants. In dry climates, however, wet weather may favor the rapid growth of wild and cultivated plants and of the insects that feed on them. In California, leafhoppers breed more readily on weeds and alfalfa, and alfalfa dwarf virus spreads more in years with higher than average rainfall. Curlytop virus of sugar beets in western U.S. is maintained in reservoirs provided by several weeds common in uncultivated land adjacent to irrigated fields. The virus is carried to beets and other cultivated crops when leafhoppers move from their winter weed hosts to the cultivated fields. During years with above normal early spring rain, a far higher proportion of leafhoppers carry the virus than in years without such early rain. Similarly, cereal yellow dwarf virus is transmitted by aphids in California. Rain delays the sowing of cereal grains but encourages the growth and subsequent aphid infestation of grasses, many of which are susceptible to the virus. When the summer dry period begins, infective aphids move from the drying grasses into young grain fields. In these two instances, a weather modification program that succeeded in increasing or prolonging the amount of spring rain for the benefit of range livestock production might simultaneously add to the disease problem on nearby cultivated cropland.

Forest Tree Diseases

The conditions required for heavy infestation of forest trees and other plants with fungal diseases are often peculiar enough to make generalizations about probable effects of weather modification almost meaningless. A series of rather special events is required for inoculum buildup of jack pine-oak gall rust in Wisconsin (Nighswander and Patton 1965). Initial infection of oak requires at least ten hours of saturated air accompanied by free water, and temperatures between 8° and 28° C. At least 13 hours of 100% relative humidity following a measurable rainfall is necessary for spore production and germination. These conditions occur infrequently and in some years not at all in central Wisconsin. Weather modification which increased the amount of rain would not necessarily at the same time produce the requisite saturated atmosphere for the time required, particularly since the critical factor is often the nature of the regional air mass.

The optimum climatic conditions for spore production and consequent infection of slash pine with fusiform rust are temperatures above 60° F., relative humidity at or near the saturation point for 9 or more hours, light surface winds and a temperature inversion at night, and showers in the afternoon and early evening. Similar air masses were present each time significant infection of pines has occurred in southeastern United States. The most important condition for spore production is the presence of a blocking ridge of high pressure in the Atlantic off the coast. Wind movement around this ridge causes spore-inducing maritime tropical air to flow into the Gulf states (Davis and Snow 1968). Modification of the large scale processes that lead to heavy fusiform rust infection is improbable in the near future.

Susceptibility to fungus infection after inoculation often depends upon the moisture status of the host. There are conflicting statements in the literature about the influence of soil moisture stress on the infection biology of the root rot *Fomes annosus* (Towers and Stambaugh 1968). Conclusions have generally been drawn from empirical correlations between disease incidence and prevailing site conditions. These correlations have suggested to various investigators that disease severity is highest in very moist or waterlogged soils, in soils inadequately supplied with moisture, and at optimum soil moisture for plant growth. Towers and Stambaugh (1968) showed experimentally that initial growth of root rot in 12-year-old loblolly pines was significantly enhanced by induced drought, but no effect of soil moisture stress could be detected 12 months later. Fungal activity had ceased by this time. However, root infection in 2-year-old seedlings was significantly higher in seedlings subjected to regular cycles of wetting and drying than in those continuously maintained in soils near field capacity. The authors suggested that alleviation of moisture stress during critical summer periods, particularly on sandy soils, may reduce incidence of *F. annosus* as a forest pest in southeastern United States.

The overland spread of oak wilt is regarded by most investigators as being the result of ascospores and conidia carried by insects. Oak wilt spreads only slowly, and in spite of the wide distribution of both the disease and susceptible trees in eastern United States, economic damage has been small. A climatic change that caused a great multiplication of the insect vectors or increased their efficiency as carriers, could transform oak wilt from a worry in much of the East to a disaster worse than the chestnut blight (Hepting 1963).

Effects of Increased Snow Accumulation and Duration

A successful program to augment snowfall for increased runoff into water supply reservoirs could alter composition of the herbaceous vegetation of the area through increased growth of parasitic fungi under the snow. Abundant and lasting snow falling before the ground is frozen creates a favorable microclimate for low temperature parasitic fungi such as *Fusarium, Sclerotinia,* and *Typhula.* If the snow is deep enough to remain on the ground well into the spring, plants are highly susceptible to injury by these snow-mold or snow-blight organisms, apparently as a result of oxygen deficiency and CO_2 excess caused by respiration under compact snow (Ylimaki 1962). Other snow molds cause extensive damage to foliage of Engelmann spruce in the Rocky Mountains, particularly on seedlings subjected to prolonged snow cover (Wardle 1968). An appreciable increase in amount and duration of snow might thus adversely affect spruce regeneration in marginal areas. The composition of the herbaceous ground cover might also be shifted toward plant species more resistant to snow-mold attack.

HUMAN DISEASES

Direct influences of weather modification on human physical or mental health are outside the scope of this report (see Sargent and Tromp [1964] for a review of biometeorological influences on human health). Some attention should be given, however, to the possible effects of weather modification on the incidence and severity of zoonoses -- diseases of animals transmissible to man. These include afflictions like Rocky Mountain spotted fever, yellow fever, and plague.

The key to human infection with most such diseases is the vector which transmits the causative organism from the animal host to man. As has already been pointed out, predicting the direct effect of weather modification on insect and other invertebrate populations is far from easy. Insect- and tick-transmitted diseases, as second order effects, are even more difficult to evaluate.

At least in the United States, weather modification seems unlikely to alter disease patterns greatly. A possible exception might be sylvatic plague, which is carried by ground squirrels and other small mammals, principally in semiarid regions. The abundance of these animals might be affected by weather modification.

As a part of any action program, a survey should be made of present and possible zoonoses in the area planned for treatment, and an effort made to evaluate how disease incidence might be affected under the specific conditions prevailing in that particular area. This is especially important if weather modification efforts extend into the tropics.

WEEDS

Weeds are the opportunists of the plant world. The species to which we attach the name "weeds" are predominantly those which can quickly colonize disturbed habitats and grow abundantly there. Weeds will surely take full advantage of the new environmental opportunity provided by weather modification.

Weed growth will undoubtedly be accelerated by weather modification wherever the changed weather factor had previously restricted plant growth. On heavily grazed rangelands, a weather modification program undertaken to improve forage production is likely only to proliferate undesirable weeds unless the weather modification is incorporated into a comprehensive plan of improved range management. Even where vegetation is in better condition, the initial response of many uncultivated grassland and shrub communities to augmented rainfall will probably be prolific growth of weeds. A planned change that makes conditions more favorable for cultivated crops will improve growth of the associated weeds; this will have to be taken into account in farm planning.

More serious might be an explosive invasion of wholly new species into an area where they had formerly not existed. This is improbable, however; appearance of weeds will instead be the result of increases, perhaps dramatic, in abundance of species already present in low numbers.

Except for introductions from other continents (e.g., cheatgrass in western U. S.), the increased abundance of plants now termed noxious has seldom if ever been the consequence of a major extension of the species' range. Instead, as in the case of mesquite invasion in the Southwest (Humphrey 1958), vegetation changes have resulted from more successful reproduction and longer survival of individuals already present as a small but evident part of the local flora. Changes in the relationships among climate, soils, grazing, and fire have, in many instances, permitted abundant growth of species formerly restricted to special sites. A similar process may be expected as a consequence of weather modification, but proliferation of altogether new pest species is improbable. The most likely exception to this statement is the possible appearance of introduced plants poisonous to livestock or other animals, which may be economically important when present even in relatively small numbers.

Many perennial weeds become established only during infrequent episodes of moisture abundant enough for seed germination and seedling growth. Once established, they survive despite rainfall too low to permit new individuals to enter the community. For instance, the noxious semi-woody shrub called burroweed increases on southern Arizona rangelands only in years of above normal winter and spring moisture.

Artificial increase of rainfall could lead to more frequent opportunities for reproduction of such species. This would no doubt increase their abundance. A simplified mathematical model presented elsewhere (Cooper In press) suggests that over the long term, the average increase in weed populations in such a situation will be approximately proportional to the increase in rainfall.

These statements are intended to describe average responses. There may well be instances where weather modification makes no observable difference in weed growth even when moisture is clearly limiting. Likewise, there are almost certain to be isolated costly outbreaks of weeds that can be attributed to weather modification. These are likely to be infrequent, however, and essentially unpredictable.

VI. DIRECT EFFECTS OF SEEDING AGENTS

Current weather modification efforts practically all depend on use of seeding agents to alter microphysical processes within clouds. The lessons of the hard pesticides should have taught us to consider physical and biological concentration mechanisms, degradability, and effects on non-human parts of ecological systems before deliberately introducing a new material into the environment.

Silver iodide is almost the only seeding agent currently used in operational weather modification experiments. AgI is 46% Ag and 54% I by weight, so that the two elements are present in nearly equal quantities.

IODINE

All available evidence indicates little likelihood of environmental effects from the iodine in AgI. A human consumer would have to drink 130 gallons of precipitation from a storm seeded with AgI to obtain as much iodine as in eggs flavored with iodized table salt. The role of iodine in physiological processes has been well documented, and instances of toxicity from naturally occurring iodine are very rare. Iodine is ubiquitous in organic and inorganic environments. Up until 1934 it was commonly produced along the Atlantic seaboard of Europe by the burning of seaweed with concomitant escape of iodine vapor to the atmosphere. Vaporized iodine was regularly detected over most of Europe during this period, but no biological effects were ever reported. It seems reasonable, therefore, to dismiss iodine in AgI at present levels of use as a source of ecological concern.

SILVER

The possible consequences of silver, in some respects the most toxic of the heavy metals, are not so easily resolved. Silver is a paradoxical substance: widely used in industry because of its great potency as a microbial poison, it is relatively harmless to higher animals, including man.

Because immediate concentrations of Ag and I in the air and rainfall will be exceedingly small, Douglas (1968) concluded that there is no direct hazard to humans from the use of AgI as a seeding agent. However, he stated that "Reconcentration through biological or botanical [*sic*] processes is not considered." It is this very reconcentration possibility that must be assayed in making predictions about the ecological effects of large-scale, long-term use of AgI.

Silver Concentrations in Rain and Snow from Seeded Clouds

The amount of AgI used in seeding operations varies according to cloud characteristics, seeding operator, purpose of seeding (i.e. hailfall retardation, lightning suppression, precipitation enhancement), intensity of seeding effort, generating device used, supporting fuel burned, ambient temperature and burning rate. Delivery rates ranging from 6 to 1500 grams AgI per hour for steady state generators and from 60 to 100,000 grams AgI per hour for pyrotechnic devices are listed in the literature. One generator is normally installed for each 100 square miles of target area.

Silver in precipitation from non-seeded storms has been measured at levels up to 20 x 10^{-12} grams of silver per milliliter of precipitation (0.00002 ppm). Silver concentrations in precipitation from seeded storms range from 0.000001 to 0.00176 ppm. Typical values are 0.0001 to 0.0003 ppm. This is of the same order as the concentration of Ag in normal seawater -- 0.00015 to 0.0003 ppm. Precipitation of this concentration would deliver 0.01 - 0.03 gm of silver per hectare per centimeter of rain.

Without known exception, ~~rare exceptions~~ there is substantially less Ag in precipitation from seeded storms than is allowed by the U. S. Public Health Service standard for drinking water. Ag in excess of 0.05 ppm is considered grounds for rejection of a water supply. The highest concentration measured in snow from the Park Range in Colorado after cloud seeding experiments, 0.00176 ppm, still falls below ~~greatly exceeds~~ the PHS standard, AND ~~but~~ most measured silver levels in snow and rain from seeded storms fall far below.

CHEMICAL ACTIVITY OF SILVER

Silver forms many different chemical compounds which differ in biological activity. This complicates the problem of interpreting data from the literature, because the chemical nature of the measured silver is seldom specified.

Silver is almost unique among metals in combining very low solubility of most of its compounds with exceedingly high toxicity of the soluble fraction. The result of these two phenomena is that silver is substantially more harmful to microorganisms than to higher animals and plants.

For silver to be toxic in low doses, the ionic form of the metal must apparently come into direct contact with metabolically active sites, such as microbial cell membranes or the gas exchange surfaces of fish gills. Ag_2S, which ionizes hardly at all, is biologically almost inactive despite its relatively high solubility. AgI, much less soluble, is biologically more active because it dissociates to form free Ag^+ ions. The activity of a specified amount of Ag is related to the concentration of silver ions rather than to the physical nature of the silver from which the ions are derived.

In contrast to other toxic heavy metals such as mercury, silver ions readily form harmless insoluble complexes with a host of biological materials. This goes far to explain the differential effect of silver salts on different classes of organisms -- why very low concentrations of soluble $AgNO_3$ are lethal to freshwater fish, for instance, whereas much greater quantities can be safely introduced into the human digestive tract or even the blood stream.

The mechanism of action apparently involves reversible chemical bonding with enzymes and other active compounds at the immediate cell surface. Very low concentrations of silver ions inhibit enzymatic activity, chiefly through binding to -SH groups. Silver and mercury are generally considered among the most specific reagents for these groups. The lipid phase of the cell membrane appears to play an important part in the mechanism of ion adsorption at the surface of living cells. The surface bonding is highly reversible; particularly with bacteria, growth resumes after removal of silver ions. An excess of silver is apparently required for significant penetration into the cell; this causes irreversible lethal denaturation.

The biological effect of silver compounds is strongly affected by temperature, oxygen concentration, presence or absence of other cations, and pH. The poor state of knowledge concerning antagonistic and synergistic effects makes it difficult to evaluate many experiments reported in the literature where these effects were not properly considered.

Silver ions are strongly adsorbed by organic colloids, plastics, glass, and other materials. Some plastic containers adsorb nearly all the silver from a solution of 0.0001 ppm and more than 20% of a 1 ppm solution in a 10-day period. Similar adsorption by the vegetation, detritus, and sediments in contact with water in streams, ponds, lakes, and marshes is likely.

LETHALITY OF SILVER COMPOUNDS

Mammals and Birds

Silver, even in highly soluble form, is only moderately harmful to mammals. 10 gm of $AgNO_3$ is usually fatal to man because of caustic action on the intestinal tract, but 3 gm can be taken without serious harm. 0.0005 mg/ml of silver have been measured in the blood after oral administration of $AgNO_3$ for intestinal disorders, with no adverse effects.

Continued intake of silver compound by mammals causes an irremediable discoloration of the skin and mucous membranes called argyria. This apparently results from the deposition of organo-silver compounds, which are subsequently reduced to a dark-colored form by sunlight. A patient with "the most generalized argyria ever reported in the literature" had the following concentrations of metallic silver: kidney 0.24%, bone 0.21%, muscle 0.16%, heart 0.15%, liver 0.07%, and brain 0.01%. There was no evidence that the silver had produced any untoward effects except discoloration. Silver granules apparently do not cause cellular reactions in adjacent tissues.

Ag^+ injected into the blood stream of experimental animals combines almost quantitatively with plasma protein. It is rapidly removed from circulation by the liver, and eliminated by the gastrointestinal tract in the bile. The silver which does not follow this pathway is sequestered in the skin and mucous tissues. The so-called blood-brain barrier specifically excludes Ag from practically all brain tissue. Unlike lead and mercury, silver does not act as a cumulative poison.

There are apparently no reports dealing with effects of silver on birds or reptiles, either with respect to adult metabolism or reproduction. The Chemistry Section of the Patuxent Wildlife Research Center, U. S. Fish and Wildlife Service, conducts routine assays of pesticide residues and heavy metals in birds and mammals from all over the United States, but they have not so far considered Ag to be a sufficient problem to justify analyses for this element.

Fish and Aquatic Invertebrates

Silver compounds are much more toxic to fish than to terrestrial vertebrates. Some of the higher concentrations of Ag recorded in precipitation from seeded storms are comparable to the lowest concentrations lethal to fish in the short run. In one set of experiments, sticklebacks were able to withstand no more than 0.003 ppm Ag in water at 15-18° C. The fish survived one week at 0.004 ppm, four days at 0.01 ppm, and but one day at 0.1 ppm. Lethalities were not stated in terms of LD_{50}, so it is not clear what portion of the population expired at various times. Nor have there been any studies of the effects of Ag on growth rates.

There seems little doubt that silver interferes with gas exchange by the gills, but the precise mechanism is not clear. Some investigators believe that Ag in dilute solution precipitates mucous secretions in the gills, filling the interlammelar spaces to the point that normal movement of the gill filaments is impossible. This prevents the intimate contact between water and gill tissues necessary for oxygen uptake, and the fish die of suffocation. Others consider the mode of action to be swelling and breakdown of gill epithelium, perhaps through blocking of enzymes. This seems more likely in view of the low concentrations that are sometimes lethal.

Virtually all laboratory tests of effects of silver on fish have been carried out with $AgNO_3$, which is presumably fully ionized at the concentrations employed. Some at least of the Ag in precipitation from seeded storms may be in particulate form, so that similar concentrations may not have identical biological effects. It is obvious, furthermore, that Ag levels in lakes and streams will reflect average, not maximum, concentrations in precipitation from all storms, seeded and unseeded, and that adsorption on vegetation and bottom sediments will further reduce concentrations in water. For this reason silver concentrations in fresh water will generally decrease with distance from the source.

Threshold concentrations of Ag toward aquatic invertebrates were 0.03 ppm for *Daphnia* and *Microregma* and 0.15 ppm for the flatworm *Polycelis nigra* in one set of investigations involving exposure for 4 days at 23-27° C. Many marine invertebrates concentrate Ag relative to their environment, as will be discussed below. There is no indication that these organisms suffer as a result.

Terrestrial Plants

Silver levels required to induce direct damage to higher plants are many times greater than will occur in precipitation from seeded storms. In one of the few known studies of the subject, Clark (1899) reported that Ag in a concentration of about 9.8 ppm was fatal to maize, and 4.9 ppm was fatal to lupines.

Microorganisms

Silver is highly toxic to microorganisms, a property that is widely exploited in industry. Minimum effective concentrations are somewhat hard to come by, since most of the literature deals with germicidal properties of silver compounds rather than with threshold levels required to achieve a detectable effect.

Many investigators have placed Ag at or near the top of the list among heavy metals in toxicity to fungi, slime molds, and bacteria. Water containing 0.0015 ppm Ag from contact with specially prepared metal has exhibited bacteriocidal activity. 0.006 ppm Ag has killed *E. coli* in 2 to 24 hours, depending on numbers of bacteria. Bacteriocidal activity in this context usually implies death of 99.9% or so of the cells present.

It has been suggested that Ag interferes more effectively with metabolism of anaerobic bacteria than with aerobic organisms. Evidence to this effect is not conclusive, nor is there any real information about the metabolic pathways that are affected by Ag poisoning. Both these points could be rather easily established in the laboratory. Selective interference with anaerobic bacteria could have significant ecological consequences where water is deoxygenated by organic pollution, in naturally anaerobic organic sediments, and in sewage treatment processes.

SUBLETHAL INHIBITION BY SILVER

Very little information is available about sublethal effects of silver or silver compounds. Most investigations, particularly with microorganisms, have been aimed at determining levels of silver that will kill an organism or effectively stop its growth. There do not seem to be any investigations reported in the literature dealing with effects of silver concentrations on growth rates of microorganisms or of fish, for instance.

Non-lethal inhibition is highly probable, however. 0.0051 ppm Ag immobilized *Daphnia magna* in Lake Erie water at 25° C. Water supply engineers have expressed concern that bacteriostasis by Ag may be mistaken for true bacteriocidal activity.

It has been suggested that silver adversely affects anaerobic processes in sewage treatment, but no concentrations have been cited at which this effect appears. The Office of Pollution Abatement of the Eastman Kodak Company reports (personal communication) that the levels of silver in their effluent are " . . . so low as to be inconclusive" and that no definitive tests to determine threshold levels of toxicity for microorganisms have been conducted. They noted that concentrations in water from which Ag is recovered sometimes reach 100 or even 1000 ppm with no noticeable effect on bacterial decomposition. They stated that no definite conclusions could be drawn about effects of Ag on sewage treatment because of variations in bacterial species and in the forms of the elements or compounds being tested for toxicity.

ENVIRONMENTAL CONCENTRATION PROCESSES

Much of the silver in precipitation will be adsorbed on clays and organic colloids as the water percolates through the soil. Rain and melted snow flowing over the surface of the ground as runoff or moving through subsurface layers as interflow makes little contact with soil colloids. Silver in this direct runoff will mostly be delivered to streams or lakes. Silver in precipitation falling directly upon the surface of lakes and streams is immediately introduced into aquatic systems.

Biological Concentration in Terrestrial Systems

Because of the low solubility of most silver salts and because of the tendency for adsorption of silver by soil colloids, most silver in terrestrial systems will presumably be immobilized.

Published silver burdens for terrestrial plants range from 0.07 ppm dry matter in "gymnosperms" to 9.0 ppm in "bryophytes" and even "up to several hundred" ppm in "mushrooms". Most values in the literature, however, are less than 1 ppm dry matter. Silver uptake in plants seems to be essentially passive and is determined by silver concentrations in the immediate environment. If mushrooms are confirmed concentrators of silver, however, and if they were to end up on a human consumer's table, the possibility of human accumulation exists. This is a point that should be investigated further, although for reasons previously stated the ingested silver would probably not be seriously harmful.

Silver burdens in the literature are even scarcer for terrestrial macrofauna than for plants. Values of 0.16 to 0.8 ppm dry matter have been recorded in the shell of the land snail *Unio mancus*, and 0.05 to 0.7 ppm in the animal's flesh. Levels between 0.005 and 0.04 ppm dry matter have been cited for various soft tissues of mammals. There is no information on other land fauna nor is it at all evident who the specific investigators were, the techniques they used nor the animals analysed.

Because most land plants do not take up silver actively there is little likelihood of silver concentrating through terrestrial food chains, nor of danger to terrestrial plants or animals if silver is used as a nucleating agent. This can be said with respect to both immediate effects and effects over a period of perhaps 20 years. Continuous reassessment during such an intermediate term of application should be made as new information accumulates.

Biological Concentration in Aquatic Ecosystems

Aquatic organisms do effectively concentrate silver and other heavy metals relative to their environment. Concentration factors (ppm in fresh organism/ppm in sea water) of 240 for brown algae, 210 for diatoms, 330 for mussels, 2300 for scallops and 18,700 for oysters have been reported. The silver content of samples of ascidians, sponges, jellyfish, anemones, sea urchins, sea slugs, starfish, wrasses, and dogfish sharks from the North Sea indicates a mean concentration factor of 22,000 compared to the silver content of surrounding sea water. Black Sea diatoms, copepods, and arrowworms all concentrate silver relative to their environment. There has never been any indication that marine organisms which concentrate silver suffer in any way as a result.

Virtually all of the available data for silver concentrating mechanisms in aquatic systems are for marine organisms. This is largely because most such measurements have been made in connection with studies of marine geochemistry. Brooks and Rumsby (1965) suggest the following pathways for concentration of trace elements by marine molluscs: (a) particulate ingestion of suspended matter; (b) ingestion of elements previously concentrated in food organisms, (c) complexing of metals by coordinate linkages with appropriate organic molecules; (d) incorporation of metal ions into physiologically important systems; (e) uptake by exchange, as for example onto mucous sheets of the oyster. With appropriate modifications, most of these processes might also occur in fresh water.

BIOLOGICAL EFFECTS ON ECOSYSTEMS

The data available in the literature indicate that there is little likelihood that silver from cloud seeding will adversely affect terrestrial plant and animal communities or marine environments, either immediately or after some 20 years of AgI application. Such a statement is clearly risky; a similar survey of pesticide effects 20 years ago would almost certainly not have anticipated the relatively recent discovery that DDT reduces the thickness of bird egg shells, and thereby lowers the reproductive rate of many bird species. Similar unforeseen metabolic effects of silver may appear, but we believe that they are unlikely.

Direct lethal effects on freshwater fish are also unlikely, either as a result of detrimental levels of silver in the water or of ingestion of harmful silver compounds concentrated through the aquatic food chain. There is a possibility, however, that there may be sufficient silver in some fresh waters, especially at the headwaters of streams, to slow the growth of susceptible fish or of the aquatic invertebrates upon which they feed. Laboratory experiments, under simulated field conditions, should be undertaken to determine the effects of very low levels of silver compounds on growth rates of fish and of representative classes of insect larvae. Consideration should be given in designing such experiments to the chemical nature of the Ag compounds used, and to the likelihood that much of the silver will be removed from solution by adsorption on vegetation surfaces and bottom sediments.

Perhaps the most likely possibility is that adsorbed silver will inhibit the growth of freshwater microorganisms -- algae, fungi, and bacteria. If such an effect does occur, it is more likely to be a selective reduction in growth of certain organisms than a dramatic lethal response. This would be detrimental if the affected microorganisms serve as food for larger animals. More serious would be interference with biological decomposition of bottom sediments, particularly in lakes and ponds. This decomposition process is a vital link in the cycle that returns essential nutrients to the water. Similar inhibition might affect sewage treatment processes, but this is less likely because of the rapid turnover and close control in such systems.

A Natural Field Experiment

Some indication of the effect of silver compounds on freshwater ecosystems, and particularly on aquatic invertebrates, might be obtained from a limnological survey of springs and spring-fed streams in the area around Fairplay, Colorado. Routine geochemical analyses by the U. S. Geological Survey have identified springs in this well-known silver mining region that have unusual concentrations of silver compounds, and which apparently lack the sulfur mineralization so common in mining regions. A comparative study of the limnology of springs with high and low levels of silver is recommended.

ORGANIC SEEDING AGENTS

Although AgI has to date been the principal nucleating agent used in weather modification experiments, it is not the only such agent. Other compounds may largely replace it in the future, mainly because of the high cost of silver and the demands that widespread application of AgI might place on the silver market.

The advantage of AgI is not only its capacity to induce ice crystal formation at relatively high temperatures, but the ease with which it can be finely subdivided. Minute particles of AgI smoke are readily carried in updrafts to cloud bases, and small quantities initiate crystallization. No other known compound so well combines these two properties.

Substantial progress in weather modification will probably depend on more precise identification of productive clouds, and on better systems for delivery of the nucleating agents to the right place at the right time. As more reliance is placed on pyrotechnic devices, aircraft, and other aerial delivery schemes, and less on ground generators, AgI may lose its importance as a seeding agent.

Several organic compounds are effective as ice crystal nuclei at temperatures warmer than the critical temperature for AgI. Phloroglucinol, 1,5-dihydroxynaphthalene, and metaldehyde have been suggested, but so far have been used only experimentally. These compounds cannot be subdivided as finely as AgI without incurring unacceptable sublimation losses, hence they cannot be efficiently dispensed from ground generators.

Organic compounds would be acceptable seeding agents only if they were degraded quickly enough that they would not accumulate in the ecosystem, and if they were initially non-toxic in the quantities present in precipitation. Of the agents mentioned, metaldehyde is the only one that appears to offer any problem. This compound is used as a snail and slug poison, and FDA standards permit no measurable residues on raw agricultural commodities. Neither 1,5-dihydroxynaphthalene nor phloroglucinol is listed in standard pesticide handbooks.

Fog Dispersal Agents

Common salt and various organic compounds have been used to disperse warm fog over airports. About 90 kg of NaCl is needed to clear a zone 500 m wide, 100 m high, and 2000 m long. Five such applications per hour, or about 450 kg/hr, would be required to keep a fogged-in airport continuously open with normal winde (Jiusto et al 1968). This amount of salt would be highly toxic to vegetation and to life in streams and lakes reached by runoff from paved runways. However, slat is so toxic to aircraft and other machinery that it almost certainly will not be used in this way (W.B. Beckwith, United Air Lines).

Recent fog dispersal tests have involved proprietary compounds identified only as "polyelectrolytes and surfactants". As a matter of public policy, authorities should without question require full disclosure of the nature of this or similar material before authorizing its use on any but an experimental basis. The time has passed when dispersal of unidentified material into the environment can be permitted after no more than a tenuous showing that it is not directly and immediately harmful to human health.

(Detailed literature citations are included in an article being prepared for submission to an appropriate technical journal, probably Water Resources Research.)

VII. BIOLOGY OF STREAMS AND LAKES

A principal objectives of weather modification will be to increase inflow into water supply reservoirs. Reservoirs and the streams that feed them provide significant recreational opportunities, among which fishing is particularly important. Fish populations, critically dependent on their habitat, are almost certain to be affected by changes in water regime brought about by weather modification. The effect will often be beneficial; stabilization of flow, with consequent reduction in the duration of critical low water periods, will generally improve conditions for fish. In other instances, fish and their habitat will be adversely affected.

The effect of weather modification on fishery resources will differ markedly from one area to another. The response of streamflow regimes and lake levels will depend upon local climatic conditions and weather modification strategy. Likewise, a given change in hydrologic conditions will affect fish populations differently, depending upon the species involved and their habitat conditions. A sustained rise in water levels during June may be beneficial in one situation and detrimental in another.

Therefore, in any area having significant fishery resources, a comprehensive aquatic survey should be a part of the advance planning carried out prior to weather modification. This survey should proceed in two parts: a hydrologic analysis to define the present water regime and the anticipated changes to be produced by weather modification; and an analysis of the probable effect of the altered hydrology on the ecology of the area's lakes and streams.

STREAMS

The effects of weather modification on the biology of streams can best be categorized according to the hydrologic changes likely to be produced. These changes will differ accordingly as the weather modification is directed primarily toward increase or decrease of winter snowpack, of summer rain, or toward some other objective.

Temperature

Increased flow generally means decreased water temperature. This in turn may affect the distribution, growth, and productivity of fish populations through alterations in the physiology of the fishes themselves, in their behavioral responses, or in their food supply.

The resistance of fish to thermal stress is strongly dependent upon the temperatures to which they were previously exposed. Fish acclimatized to low temperatures cannot endure as high a temperature as those acclimatized to high temperatures and vice versa. Thermal acclimatization of fishes usually requires one to three days. Even if total flow were somewhat augmented through weather modification, temperature changes in unregulated streams would be gradual enough to allow some acclimatization. However, if the additional water were stored in impoundments, an abrupt temperature change caused by sudden discharge of deep, cold water into streams during summer may cause mortality of fish. This could be avoided by gradual increases in release over a period of a few days.

Certain life history stages may be more susceptible to temperature extremes than others. Adult brown trout and brook trout can tolerate temperatures of 0° C., but eggs and alevins of these species require somewhat higher temperatures for successful development. Very low but non-lethal temperatures may so retard development that the young emerge very late in the fall and face a very low probability of survival through their first winter. Such effects obviously depend upon the coincidence of unfavorable environmental temperatures and the sensitive life history stage of the fish.

Some species are limited by behavioral traits and by interspecific competitive disadvantages incurred at certain temperatures to a zone within a stream narrower than that set by the limits of physiological tolerance to temperature extremes. The Logan River in Utah is typical of many mountain streams in western U. S. The upper reaches support a good trout population; the lower portion is inhabited by carp, suckers, and other unwanted warm water fishes. The boundary between the two groups is determined by temperature; in high flow years it moves downstream, and in low flow years it is as much as several miles farther up the river. This is apparently an immediate behavioral response, not one involving a long period of adjustment to changes in food conditions. It is likely, however, that the distribution of trout at any given temperature would extend further downstream if no warm water fishes were present. The trout are better able to compete for food and space at lower temperatures and the warm water species are more successful at higher temperatures, so thermal effects on distribution cannot be considered apart from competitive effects of species on one another.

Within the preferred temperature range of a species there are still more subtle temperature relations which may have important effects upon survival. For example, recently emerged rainbow trout fry make frequent contact with the stream bottom when water temperatures are above 15° C. This enables them to maintain their position in the stream against the force of the current even in darkness. At temperatures below 13° C, the fry rarely make contact with the substrate, and so are unable to remain oriented to a particular site in the stream when they lose visual positional cues. As a consequence they are carried considerable distances downstream by the current at night. A few degrees drop in water temperature, resulting from a prolonged period of melt water runoff in a region where weather modification had substantially increased snow pack, could result in displacement of young fish from a nursery area to downstream areas. In natural situations, such temperature effects probably control migration of young trout from tributary streams into lakes where they thrive and produce excellent fishing, and such effects could be taken advantage of in management of fisheries in areas subject to weather modification. In some circumstances, however, small temperature changes could displace young fish to totally unsuitable environments, and ultimately decimate stream populations.

Large fry and fingerling rainbow trout respond to rapid rises in water temperature by moving upstream. This may enable them to escape intolerably high temperatures, but may carry them into headwater areas where protective cover is scarce and exposure to predation is increased. Maintenance of preferred temperatures for gamefish in downstream areas by prolonged runoff of snow melt water or release of cold water from storage impoundments would tend to maintain populations in larger, usually more protective waters. Disadvantages might arise where induced hydrological or meteorological changes eliminated rapid temperature rises which, under natural conditions, triggered upstream movement of fish from outlets into lakes where more food and space is available to them. Where substantial loss of fishery values resulted, remedial management, such as stocking of depleted waters, often could be undertaken at reasonable cost.

The duration of the various stages in the life cycle of many aquatic insects is strongly influenced by water temperature. These effects may be translated into responses by fish population which prey upon the insects. For example, mayflies and other aquatic insects, which comprise the major food supply for fish in the Colorado River under normal circumstances, almost completely fail to complete their life cycle in river stretches below major dams when colder than normal water is released during summer. This effect often extends for several miles below each dam, and fish populations are correspondingly depleted.

Stream Velocity

Depending upon local climatic conditions and the weather modification strategy employed, there is likely to be an appreciable increase in sustained flow at certain times of the year, possibly accompanied by an increase in flood peaks, with relatively little change in stream flow at other times. The manner in which these changes affect populations of aquatic organisms depends upon the nature of the alteration in channel shape and flow velocity, on the timing of flow changes in relation to particularly sensitive life history stages of the biota, and on direct responses of living organisms to changes in stream velocity.

The physical configuration of a water course is determined by the interaction of erosion and deposition processes with the materials which make up the banks and bed of the stream. Where stream banks are resistant to erosion the stream digs a relatively deep, narrow channel. Pools and riffles are produced in straight channels by undulations of the stream bed which form alternating deep and shallow stretches at a repeating distance of five to seven channel widths. In sinuous stretches, pools are formed by erosion of deep pockets near the concave bank of each curve of the channel. The length of meander in sinuous streams is closely related to channel width, producing nearly the same spacing of alternating pools and riffles as occurs in straight stretches of streams.

An intricately developed physical habitat, with frequent alternation of pools and riffles, a highly sinuous stream channel, and abundant obstacles such as cobbles, boulders, and logs, is capable of carrying many more fish per unit area than a relatively monotonous environment. In addition to the obvious advantages of protection from strong currents and from predators, obstacles such as logs and rocks shield the fish, which tend to be aggressively territorial, from one another's view, thereby providing more but smaller individual territories per unit area of stream.

Water velocity has direct effects upon the ecology and behavior of fishes. At high flow velocities, the territory defended by salmonid fishes tends to be smaller, they display a greater affinity for physical cover, and competitive interactions may change in intensity and frequency. Some of these effects have been documented for particular species but many others, important in predicting the biological results of increased stream flows, must exist as yet undiscovered.

The scouring of channels which often accompanies increases in stream velocity, and even more the alternating scouring and sedimentation which is caused by widely fluctuating velocities, pose serious problems for aquatic organisms. The benthic invertebrates which constitute the most important source of food for most stream fishes are extremely sensitive to mass movements of the substrate. At low water temperatures in late winter and early spring, many small fish take cover in the interstices of coarse gravels, and may be crushed to death by movement of the substrate during freshets. The eggs of salmonids, which are buried in the gravel of the stream-bed during incubation, are extremely sensitive to scouring and to siltation. Large fluctuations in stream levels, if not properly synchronized with the life history of the fish, may lead them to spawn in temporarily inundated areas where the eggs will later be exposed to freezing or dessication.

Special habitat conditions are required for the fry and juvenile fish of some species. Young salmonids, for example, after emergence from the gravel begin active feeding in relatively quiet waters along the margins of streams. The amount of such habitat available for young fish in torrential habitats might be a factor limiting the size of the population, even though adequate habitat for larger fish existed.

Stream fishes, possessing well developed locomotor ability, are able to compensate for down-stream displacement by extensive up-stream migration where necessary. By contrast, the invertebrate fauna of flowing waters is able, in the aquatic stages, to effect only modest up-stream movement because of their limited locomotor powers. In populations of aquatic insects up-stream flight by the winged adults during breeding and egg laying is believed to counteract the tendency toward downstream displacement of the immature stages by the current. The balance between downstream displacement and compensating upstream movements may be a delicate one for some species, and increases in peak or sustained stream velocities resulting from weather modification might result in a marked shift in species composition of the invertebrates upon which game fish depend. If displaced species are replaced in their original habitat by expanded populations of companion species or by newly introduced species, productivity of food organisms would not be diminished by increases in flow velocity. If such replacements were not made the productivity of streams under increased velocities might be diminished to the detriment of fish populations.

Many invertebrates are loosened and moved in riffle areas or are flushed out of previously slow and shallow backwaters near shore by increased stream flows. This phenomenon has been observed following the first fall rains after a long dry summer with low stream flows. No comparable data on movements of invertebrates during snow melt freshets seem to be available. Sudden reductions in stream discharge have also been shown to increase the amount of invertebrate drift. The downstream transport of invertebrate organisms in streams seems to be a universal phenomenon, exhibiting a marked diurnal pulse, and taking place even in the absence of abrupt changes in stream flow. It disperses the organisms, which may be beneficial, but also exposes them to the risk of deposition in habitats unsuitable for completion of their life cycle.

Drift organisms constitute an important fraction of the diet of many stream fishes, and any condition which increases the amount of drift may increase the availability of food to fish populations. The phenomenon of invertebrate drift in particular, and the population dynamics of stream-dwelling invertebrates in general, are not well enough understood at present to allow confident prediction of the impact of changes in stream flow upon abundance of food organisms or the feeding relations of fish.

Increase in Low Flows

Periods of low stream flow are often accompanied by critically low or critically high temperatures, depending on the season, and under conditions of high temperature, by critically low levels of dissolved oxygen. Augmentation of streamflow at such critical periods could bring into production areas of stream not otherwise capable of supporting populations of sport fish.

Increased flows within existing channels will result in increased stream width and/or depth, depending upon the cross sectional shape and constituent materials of the channel. The resulting increase in bottom area represents an additional source of primary and secondary productivity, which can be utilized by fish populations. The importance of this addition in bottom area in increasing biological productivity will depend upon the season and duration of inundation, the substrate materials, and channel shape.

Low stream flows confine fish to a smaller environment, frequently expose them to intensified predation, and may seriously restrict spawning migrations. For some species of fish the dimensions of the immediate environment affect the rate of growth. Decreased water velocity and turbulence, which often accompany low flows, lead salmonids to defend larger territories, and hence reduce the fish-carrying capacity of each unit area of stream. The total fish production of a stream may be limited by the reduction in habitat which accompanies a relatively short period of very limited flow, and augmentation resulting from weather modification could substantially increase the productivity of such streams.

Turbidity

Erosion caused by surface runoff or increased stream velocity may cause substantial increases in turbidity. However, at levels likely to be encountered under natural conditions, turbidity usually does not cause mortality or physical damage to fish.

In laboratory studies of the direct effects of montmorillonite clay turbidity on 16 species of warmwater fish, behavioral reactions were usually not observed until levels approached 20,000 ppm (as SiO_2), and mortality occurred only at turbidities well in excess of 50,000 ppm. Most of these experimental fishes tolerated exposure to turbidity greater than 100,000 ppm for a week or more.

Turbid water, by decreasing the penetration of sunlight, may reduce the photosynthetic activity of algae and higher aquatic plants. Reduced visibility interferes with the feeding behavior of animals which are primarily sight feeders, including a majority of the most popular sport fishes. Species which rely upon visual cues for maintenance of position in streams may be displaced into unsuitable habitats under conditions of high turbidity. The vulnerability of fishes to predation may, however, be reduced during periods in which the water is turbid. Silt deposits may smother bottom-dwelling invertebrates which are adapted to a rock and gravel substrate, and the eggs and alevins of salmonids, which undergo incubation in stream-bed gravels.

Terrestrial Organic Matter as an Energy Source

A substantial share of the biochemically fixed energy used by aquatic invertebrates, and eventually consumed by fish, has its source on land. Leaves, seeds, animal droppings, terrestrial insects -- all in various stages of decomposition and breakdown -- are washed into lakes and streams. They are consumed directly by aquatic invertebrates, or used as substrates by the aquatic bacteria and fungi upon which these organisms feed.

Increased precipitation, if accompanied by increased overland drainage, may add to the amount of this terrestrial material entering streams. However, increased scouring caused by higher stream flows might tend to remove such materials from the aquatic environment. The balance between addition and removal will depend upon the source and nature of the organic material, and upon the physical properties of the stream which determine its ability to accommodate increased flows without excessive scouring.

Snow and Stream Freezing

Under conditions of very low air temperatures and high radiant loss of heat, ice may form on the bottoms of streams. These ice masses frequently tear loose and float downstream, carrying and subsequently redepositing the substrate materials they have incorporated. Considerable damage to aquatic organisms may result from abrasion, freezing, and disruption of the substrate.

Increases in winter precipitation, as a result of weather modification, might be sufficient to bridge small streams with an insulating layer of snow and reduce the damage caused by ice formation. Excessive snowfalls, however, can produce snow and ice dams which divert stream flows, leaving fish stranded and eggs and aquatic invertebrates exposed to dessication and freezing.

Chemical Quality of Water

There are a few places, particularly in the semiarid West, where stream salinity is high enough to pose a problem for fish and other aquatic organisms. Although it has regularly been shown that mineral content is inversely related to average stream discharge per square mile of drainage basin, it is not likely that the chemical quality of water will be greatly improved as a result of increased flow engendered by weather modification. The additional precipitation will presumably leach more soluble salts from the watershed, so that the average concentration in the runoff water will not be greatly reduced. The aggregate salt removal will in fact be increased. In more humid climates, the previously discussed data from Hubbard Brook and elsewhere suggest that the concentration of beneficial nutrients in runoff water will not be greatly changed as a result of weather modification.

LAKES

Much of the additional runoff generated by weather modification will be stored in reservoirs for release to satisfy later demands. Where this is the case, the effect on aquatic ecology will depend almost entirely on the water release policy adopted by the operating agency. Some or all of the added water might be used to provide more flexibility in release policies, so as to avoid drastic lowering of water level. This would be wholly beneficial to aquatic resources. On the other hand, if reservoir management policies paid little attention to fish, no benefit would accrue. Conflicts are inevitable over proper allocation of water generated by weather modification, and public attitudes today are such that recreation interests may win out over older, more traditional uses. It is not improbable that weather modification programs will be advocated specifically to improve recreational aspects of multiple use reservoirs.

Water movement is less effective in flushing dissolved minerals and terrestrial detritus from lakes than in streams, and deposition of suspended materials is greater in lakes. Weather modification might have a minor effect on lake temperature if there were a substantially increased inflow from melting snow, particularly where rivers are short and steep. Turbidity of lake water might be increased if tributary streams carry high silt loads for long periods.

Additional snow cover on lakes which chronically experience borderline oxygen depletion in winter might be enough to reduce the photosynthetic activity of aquatic plants, by further reducing light penetration, to the point where more frequent or severe oxygen depletion occurred. An opposite possibility is that

of averting oxygen depletion by increasing lake levels through additional precipitation. Either of these possible effects would be expected only in lakes which were on the borderline of oxygen depletion before the induced changes in precipitation pattern.

VIII. FOG, HAIL, LIGHTNING, AND HURRICANES

FOG

Fog dispersal, particularly over airports, is probably the first form of deliberate weather modification technically and economically feasible for wide application. The meteorological and economic aspects of fog have been well discussed in a recent article in *Scientific American* (Myers 1968).

It is difficult to see any significant ecological effect from foreseeable kinds of fog dispersal. Airports in the U. S. are closed by fog an average of 115 hours per year; many of these hours are at night or in winter when biological processes are slowed. Of course, some regions have much more fog than the average, but the foggiest areas are likely to be the hardest to control. Fog dispersal will almost always be highly local; there is little present likelihood that fog and low stratus can be continuously enough dispersed over wide areas to affect the surface heat or radiation balances.

United Air Lines claims 80% success in dissipating supercooled fogs with dry ice or liquid propane, but supercooled fogs account for only about 5% of all fogs in continental U. S. outside Alaska, and they occur only in winter.

Warm fog dispersal is more difficult, although experiments at Sacramento, primarily with radiation fog, have been promising (Flynn and Beckwith 1968). Additional experiments with advection fog are being conducted at Cape Cod and Nantucket Island. Indications are that warm fog dispersal will be expensive, and will be practiced only where economic costs associated with fog are high.

Fog has been identified as an important ecological factor only in maritime situations such as the redwood forests of California or the coastal deserts of Peru, and in the cloud forests of certain temperate and tropical mountains. There will not soon be either the technological capability or the economic motivation to alter fog patterns over these areas in a major way.

HAIL

Hail may also be controllable (Schleusener 1968). The principle of hail suppression is to induce precipitation to fall sooner than it normally would, or perhaps to restrain it entirely by massive overseeding. Success depends upon quick recognition of potential hail-producing clouds, and efficient delivery of seeding material to the cloud after it has been identified.

These requirements will presumably limit operational hail suppression activities to regions of frequent damage, because of the cost of manpower and equipment that must constantly be ready on a standby basis. These areas are likely to be principally in the farming zones of the Great Plains.

There are many references in the literature to losses of nesting birds, eggs, and young from hail, but there have apparently been no comprehensive analyses of hail as a factor in the structure of natural ecosystems. It is hard to see how hail suppression could be anything but beneficial to ecologically interesting and valuable species, unless it is accompanied by a substantial change in rainfall.

LIGHTNING

Experiments conducted by the U. S. Forest Service have shown promise of reducing the incidence of lightning and of lightning-caused forest and range fires. Because of the recognized role of fire in the development of natural vegetation, concern has been expressed that ". . . if fire could be controlled through weather control, competitors would likely march in from the boundaries of many coniferous forests and of many grasslands, slowly converting the habitat" (Waggoner 1966). This is something of a non sequitur; fire prevention and suppression efforts of land management agencies have already effectively removed fire as a natural ecological factor. Prescribed and controlled fire may in many instances be a useful ecological tool, and it can be argued that prescribed fire should be more widely used in land management. The transition from extensive to intensive land management, however, and the continuing increase of private homes and other property in areas of fire danger virtually compel land management agencies to prevent natural fires or to extinguish them as soon as possible if they cannot be prevented from starting. It is unrealistic to object to such efforts on presumed ecological grounds under present conditions.

HURRICANES

Significant control over hurricanes will be far more difficult than modification of fog, hail, or lightning. If successful hurricane control should be achieved, however, the ecological consequences would be profound.

The almost unbelievable energy of a hurricane makes a frontal assault impossible, but meteorological theory suggest that selective seeding of the right part of the storm system at the right time may trigger energy changes sufficient to alter the course of the storm (Battan 1968). It will hardly be possible to prevent tropical storms from forming at all; indeed, even if it were, such a course would prove disastrous. Hurricanes are one of the principal mechanisms that transport large quantities of heat toward the poles, helping to maintain the earth's heat balance (Miller 1967). Consistent restriction of this mechanism by complete storm dissipation would presumably lead to one of two situations: oceanic and terrestrial temperature regimes and circulation patterns would be altered over much of the world, or the accumulated energy would ultimately escape in an uncontrollable storm of unprecedented ferocity. These points are familiar to meteorologists, but perhaps not to those of the lay public who talk glibly of total hurricane control.

The most that can be expected is a reduction in sustained peak wind velocity. A reduction of hurricane winds from 120 miles an hour to 80 would enormously reduce property damage and loss of life from tropical storms, even though an 80-mile wind is far from innocuous. Associated with such a reduction would be ecological changes that can be discussed under three categories: direct wind effects on terrestrial ecosystems, precipitation changes on land, and changes in the marine environment.

Wind in Terrestrial Ecosystems

The hurricane of 1938 blew down millions of board feet of merchantable timber throughout the New England states and virtually wrecked the log market for several years thereafter. This was apparently not a unique event. Raup (1956) has called attention to the patchy nature of the original forest of New England, which he attributes mostly to past hurricane blowdowns. By dating the trees growing on mounds formed by uprooting of previous generations of trees, it is possible to determine the time of previous hurricanes. In New England, the frequency appears to be about once a century. Since the major tree species have a potential life of 300 years or more, it is not very meaningful to speak of a stable or climax vegetation at the time of white settlement, when severe disturbance has apparently occurred at regular intervals much shorter than the trees' potential longevity.

Whatever the value of this analysis as an explanation of the structure of New England forests in the last century, it is not appropriate to suggest that hurricanes of 1938 severity should be allowed to recur at unpredictable intervals simply to maintain the diversity of the New England landscape. Land clearing in the nineteenth century did much to destroy this diversity; reversion to forest is restoring it today. Knowledge of the role of hurricanes as a formative influence in early New England vegetation is useful in that modern management techniques may, if desired, be used to simulate wind effects. It is neither necessary nor desirable, however, to depend today upon wind at century intervals in creating a pleasing and productive landscape.

The situation may be different in the Caribbean Islands, the spawning grounds of hurricanes, where destructive winds may hit a given area every twenty or thirty years rather than once a century. On St. Kitts, Beard (1949) observed signs of distant past storms in the lower montane forest. All large trees seemed to fork at 20 to 30 feet, whereas smaller and presumably younger trees did not. Similarly, the greater part of the forest in the mountains in the southern part of the island of St. Vincent is of subclimax type owing to the regular hurricanes which periodically destroy large trees and thus prevent development of climax montane rain forest (Beard 1945).

The valuable kauri forest of the Solomon Islands likewise survives because of hurricanes (typhoons). Kauri trees grow principally on ridgetops, and seedlings become established only after moderate disturbance such as that resulting from hurricanes or landslides. Properly planned felling operations can simulate these conditions, assuring kauri regeneration (Whitmore 1965).

The gains in human life and saving of property that could be achieved through a substantial reduction in hurricane intensity would surely outweigh any possible adverse long term effects on the natural or semi-natural vegetation of subtropical islands. Nevertheless, such effects may occur, and the Solomon Islands example suggests that appropriate management procedures can minimize them. A survey should be made, on the ground and with aerial photographs, of the vegetation of several Caribbean Islands regularly exposed to hurricanes. Surveys should be made along and adjacent to storm tracks of known age. The objective would be to determine the fraction of the non-cultivated vegetation that has apparently been subjected to varying degrees of wind disturbance. In the event that hurricane control becomes feasible, plans should be laid to retain approximately the present vegetation mosaic through artificial stand manipulation. The alternative, in the absence of course of further deliberate forest clearing, will be development of a more uniform forest than that of today, offering less biological and esthetic variety for human enjoyment.

Precipitation

Tropical storms are responsible for a substantial share of the precipitation reaching the eastern seaboard of the United States, particularly from June to October. Studies reviewed by Sargent (1967) suggest that the fraction ranges from 13% along the South Atlantic coast to over 30% in the Middle Atlantic and Gulf Coast regions. Marlatt (1967) has shown that annual rainfall amounts at New Brunswick, N. J., have a distinctly bimodal distribution. The second of the two peaks is due to those years in which tropical storms bring heavy rain to the area. According to Marlatt's calculations, almost 40% of the average April-September precipitation at New Brunswick is due to tropical storms.

Tropical storm rainfall decreases rapidly with distance from the shore. The size and wind intensity of the cyclonic disturbance largely determine how far inland significant rainfall can penetrate. Artificial reduction in intensity of tropical storms might therefore decrease the amount of rainfall east of the Appalachians and in the Gulf Coast region, with consequent adverse effects on crops and natural vegetation.

Simple estimates of the proportion of the average precipitation brought to any area by tropical storms are not very helpful, however. These storms typically are infrequent but bring large amounts of rain when they do occur. Long term averages may therefore be distorted to the extent that four or five separate two-day events over a thirty-year span may account for an appreciable fraction of the computed mean annual rainfall. Much of this rain may have run off over the surface, perhaps causing substantial erosion in the process. Reduction of tropical storm intensity may decrease rainfall inland largely through loss of a relatively few near-flood events. If this is the case, the decline in mean annual precipitation would be less serious than simple inspection of the averages would suggest.

A climatological and hydrologic study based on simulation models is necessary to determine this. Data from a number of locations along the eastern seaboard and at varying distances inland should be fitted to the Stanford Watershed Model (see Chapter XI). Given the appropriate data on basin characteristics and rainfall amounts and intensities, this model can estimate the allocation of rainfall to runoff and basin retention. Rainfall sequences with and without tropical storms can be tested on the computer to predict the effect of weather modifidation. A meteorologist would necessarily be a member of the team to derive estimates of the effect of hurricane modification on rainfall probabilities at any given point. The basin retention component can be fed into the Michigan Soil Moisture-Transpiration model (Chapter XI). to estimate the effect of weather modification on transpiration and assumed plant growth. It is important that a comprehensive simulation study of this sort be undertaken before an extensive hurricane modification program is started. It would not be surprising if such a study showed that, because of the relative infrequency of tropical storm rains, the greatest effect was on streamflow and reservoir storage rather than on ecological conditions mediated by soil moisture.

It has been suggested informally that reduction in frequency of near-flood rains might have a detrimental effect on stream biology -- perhaps streams along the eastern seaboard need an occasional "flushing out" to keep them biologically healthy. No limnologist with whom the subject has been discussed believes this to be so. On the contrary, excessively high flows are generally damaging; their elimination would aid stream management.

Marine and Shoreline Environments

This topic is given only a cursory examination here, but it should be thoroughly reviewed before an operational hurricane control program is undertaken.

The temperature structure of the ocean is significantly affected by hurricanes. There is evidence of upwelling from a depth of 200 feet or more near the storm track. Surface temperature decreases of 2° to 5° C. have been noted. Downwelling occurs at a distance from the storm track (Landis and Leipper 1968).

Great increases in lobster populations have been observed in the Florida Keys after rough seas and high tides caused by hurricanes. It is thought that immigration takes place from great distances or from depths which are normally inaccessible to fishermen (Sugg 1968).

Hurricanes frequently alter coastal morphology, including coral reef structure. Although such events may be catastrophic in terms of man's longest period of observation, his lifetime, they are only commonplace events in the scale of geologic time (Ball et al 1967). These regular catastrophes, however, do presumably keep the inshore biological communities stirred up and in a continual state of flux. The same is true of such coastal communities as mangrove, whose biology is regularly affected by severe storms (Sauer 1967).

IX. MONITORING THE EFFECTS OF WEATHER MODIFICATION

An essential part of any weather modification program should be regular field measurements to identify unanticipated biological effects and to assess responses that had been predicted beforehand. Plant and animal communities will in general respond rather slowly to weather modification, but the cumulative effect over a period of years could be a fairly drastic alteration of original conditions. A monitoring system should be designed to detect incipient change at an early stage, and to make predictions about possible irreversible change early enough that management policies can be altered in time.

The problem of monitoring the ecological effects of weather modification is an integral part of the problem of assessing ecological changes brought about by the whole range of advancing human technology. A program to assess the consequences of weather modification should be planned, not in isolation, but in conjunction with other environmental assessments.

PROPOSALS FOR ECOLOGICAL SURVEY AND ENVIRONMENTAL MONITORING

A national program of ecological surveys and environmental monitoring has been proposed from several quarters. Bills to this end have been introduced in Congress by Senators Nelson and Jackson and by Representatives Dingell and Tunney, among others.

In his message to Congress on Natural Beauty on February 8, 1965, President Johnson asked the Directors of the Office of Science and Technology and of the Bureau of the Budget to recommend "how the Federal Government may best direct its efforts toward advancing scientific understanding of natural plant and animal communities and their interactions with man and his activities". These agencies responded on January 24, 1968, in a Memorandum for the President signed by Charles L. Schultze and Donald F. Hornig, Directors, respectively, of the Bureau of the Budget and the Office of Science and Technology in the Executive Office of the President. Accompanying the Memorandum was a report based on the findings of a panel of experts from Federal agencies assembled by OST. The report stated in part:

> Comprehensive documentation of the nature, abundance, distribution, diversity, and condition of the components in a limited number of representative areas is needed to provide points of departure for measuring future changes in natural communities. Data from de-

> tailed benchmark studies provide a basis for further programs in research and monitoring and comprise an inventory of the related factors in a functioning natural system. From the standpoint of research they are points of departure for studies ranging from such basic aspects as measurement of energy flow within undisturbed natural systems, to providing a basis for assessing the long term effects of environmental manipulation e.g. existing weather modification programs. As an essential prerequisite for monitoring, benchmark information is the "ground truth" with which the impact of expected or unanticipated environmental changes can be compared.
>
> Monitoring of all relevant biological and environmental components of representative natural community areas is needed. Work should be conducted in both undisturbed and modified areas. Favorable and unfavorable changes should be noted over time and trends identified. Additional information is needed about the effects and duration of natural biologically -- and environmentally -- induced changes in plant and animal communities and man-induced changes resulting from management practices and other activities.

The transmitting Memorandum clearly stated that "The Bureau of the Budget makes no recommendations for commitment of funds for new programs"; nevertheless, the quoted statements about documentation and monitoring of biological systems can be taken as the policy of the Executive branch at that time and presumably today.

Dealing only with weather modification and its effects, the Ecological Society of America (1966) was quite specific in proposing that selected communities should be monitored:

> In an area in which weather is to be modified, natural communities would be selected for study and permanent plots established in them. Communities would be chosen to represent the full range of environments and major community-types in the area and especially such extreme environments as ravines, dry slopes, or exposed bedrock. Before weather modification, plots of these plant communities would be mapped in detail and photographed. The plots would be restudied during, and after, a period of weather modification to determine what species have expanded their populations and what species lost ground, what species disappeared from the community and what new species entered, and whether such indexes of growth and production as the wood-rings of trees show

> altered levels of community function. The approach is one of monitoring effects on communities, with limited effort toward determining the complex meanings of these effects. Although plots observed before modification would be intended as controls, establishment of plots in similar communities outside the area of weather modification would also be essential. Statistical evaluation of such variables as tree-ring widths would be difficult at best, and without controls would be impossible.
>
> For preservation and usefulness these quadrats should be established in national forests, national parks, university research areas, or other locations subject to full protection and available to investigators interested in repeated observation of their communities.
>
> Animal communities offer much greater difficulty, first in sampling population levels, second in interpreting apparent differences in population levels. The labor involved in work with animal groups might limit such study to a fraction of the communities in which vegetation quadrats could be established. Two groups of animals may offer most promise for community monitoring -- singing birds, whose populations can be mapped and densities determined with some reliability, and the small arthropods of the soil surface, for which efficient means of extracting relatively large population samples are available.
>
> Even though complete ecological monitoring of a weather modification program is not feasible, every effort should be made to see that systematic observations are carried out. First priority should be given to those species known or suspected of being capable of damaging crops or of causing defoliation of the natural vegetation. The cost of even this minimal surveillance would be very high; the cost of not carrying it out might be very much higher. In as much as one cannot predict all of the meteorological consequences of weather modification, it would be folly to allow such a program to be carried out without careful monitoring of the biological consequences.

The ESA Panel recognized several difficulties in this sort of evaluation of the effects of weather modification on natural communities: (a) the long time-scales involved; (b) the fact that weather modification will extend over large geographic areas, each of which may include many kinds of environments and communities; (c) normal fluctuations of weather and climate, which make evaluation of the extent of man's modification difficult; (d) normal fluctuations in the populations of plants and animals which make it difficult to distinguish changes in populations brought about by weather modification; (e) the complexity and interaction of the environmental factors to be modified; (f) the great complexity of natural communities and the great variety of changes in them which might result from weather modification; (g) the difficulty of establishing an effective control area for research comparison with an area in which weather is to be modified, since no two geographic areas are quite alike in their environments and natural communities. Nevertheless, the Panel was insistent that such monitoring be undertaken.

Need for Comprehensive Study of Ecological Monitoring

Environmental monitoring systems are basically of two kinds: those designed to detect changes in the concentration of specific substances in the environment, and those designed to measure changes in the abundance of specific animals and plants in natural communities. The aim is to identify and interpret small effects not yet apparent to the casual observer.

Measurement of changes in concentration of specific substances -- sulfur dioxide or hydrocarbons in the atmosphere, DDT in the bodies of birds, or sediment load in streams -- is the easier of the two types of monitoring to carry out in practice. Analytic techniques for detection and quantitative measurement of the substances must be developed, and statistical analysis is needed to establish the validity of the results. Nevertheless, it is relatively simple in principle to design a system for monitoring changes in the amounts of substances whose presence is deemed harmful to environmental quality. The measured substances, though, are usually of interest only because they are expected to induce changes in plant and animal communities or in human health. The principal difficulty with monitoring systems of this sort is to interpret the measured changes in terms of an expected biological response.

Human health aside, the truly significant effects of environmental modification are changes in plant and animal populations. These may be slow and subtle at first, and difficult to detect. Weather modification is unlikely except in a few extreme instances to induce sudden and drastic changes in plant and animal communities. The relatively small initial effects are likely to be cumulative, however, and possibly difficult to reverse after the weather modification is stopped. Hence a well designed advance warning system is imperative.

A similar warning system is needed for environmental changes induced by other aspects of advancing technology. There is an urgent need for a comprehensive study of the best procedures for operating such an environmental monitoring system. Agencies and organizations proposing actively to modify the weather over significant areas have an obligation and responsibility to contribute heavily to the funding of such a study and to the financing of the environmental monitoring program ultimately recommended by the study team.

We do not believe, however, that a large-scale national environmental monitoring program should be started before such a comprehensive study is made. The results of an inadequately planned monitoring program are likely to be almost impossible to interpret and to translate into effective action. The disappointment shown by funding agencies at an unsuccessful program is likely to have unfortunate repercussions when better planned proposals for ecological evaluation are submitted.

This is in no sense a recommendation for inaction. It is a recommendation for a delay of a year or two in undertaking a large scale field program. This time and money can better be invested in a comprehensive analysis and planning effort to make an ecological monitoring system more effective and productive.

METHODS FOR EVALUATING FIELD RESPONSE

There are three principal approaches to field assessment of biological changes brought about by deliberate or inadvertent modification of the environment:

(1) Periodic remeasurement of population numbers, vigor, and age structure on permanent sample plots.
(2) Periodic reconnaissance surveys to detect widespread changes in animal populations, or shifts in boundaries or ecotones between plant communities.
(3) Measurement of changes in abundance, growth rate, or phenology of indicator species.

All three methods will presumable be incorporated into an operational ecological monitoring program.

Permanent Plots

Carefully standardized procedures for measurement of plant and animal populations will have to be developed and strictly adhered to. This is not particularly difficult in principle, although standardization of measurement has not been common in ecology.

Even the most careful measurements will not be easy to interpret, largely because we do not yet know what environmental stimulus evokes a given response from an ecosystem. Variations in plant and animal populations on sample plots may be a consequence of several processes: (1) Changes in the major environmental factor whose effects the monitoring system is designed to evaluate. (2) Other concurrent man-induced changes in the environment, such as air pollution. (3) Slow secular changes in climate, to which vegetation and animals are still adjusting. (4) Year-to-year fluctuations in weather. (5) Successional or other one-directional change in vegetation. (6) Normal fluctuations in plant and animal populations.

Even where vegetation appears to be adjusted to its environment, species composition on any single small area is seldom static. For example, year-to-year comparisons of maps of plant cover on permanent meter-square quadrats in the Snake River Plains of Idaho show continual change (Blaisdell 1958). One perennial species is replaced by another; areas covered by vegetation become barren, and barren areas are occupied; annuals and seedlings of perennials appear and disappear. Two parts of the community may be undergoing changes in the same direction at the same time, or what appear to be directly opposing changes may take place. Blaisdell concluded that variation and change are inherent in the apparently stable vegetation of this semiarid area, where ground cover by vegetation is seldom complete. The abundance of certain species on the area as a whole or of all species on certain microsites can change greatly without materially affecting the overall structure of the community.

Essentially the same situation exists in the denser and more abundant vegetation of the true prairie region. Even on ungrazed plots that have long been protected, there are great annual fluctuations in species composition of prairies. These fluctuations are related to unknown combinations of climatic factors (Penfound 1964). Normal variations are so great as to mask changes simultaneously induced by planned environmental change, at least until the environmental modification has been in effect for some time.

Similar examples could be multiplied from the literature, but Watt (1947) has indicated that dynamic change of this sort is a characteristic ecological property. Most plant communities are comprised of continually changing patterns of phases or patches. According to this hypothesis, the cycle of change on each small unit of landscape is divisible into two parts: an upgrade, when the net quantity of plant material is increasing and the habitat potential is improving; and a downgrade, characterized by dispersion and breakdown of plant material, mainly by fungi, bacteria, and insects. The resulting patchiness can be readily detected in most communities; although it may not be universal, it is widespread. Watt has postulated that plant communities in a constant environment will show a steady state, consisting of a definite proportion between the constituent phases. This steady state may be called phasic equilibrium. Departures from this phasic equilibrium can presumably be measured and correlated with factors of the environment.

Evidence collected in recent years substantiates Watt's hypothesis. Patches or phases are evident, for example, in both grassland and in alpine tundra, both of which are likely targets of weather modification. Little information is available, however, on the scale of pattern in space or time in most vegetation types. An experimental design that fails to take into account natural phase changes is likely to attribute plant community alterations to environmental modification when thay are in fact a normal occurrence. This is another reason why environmental monitoring programs must necessarily extend over time.

Population variations in space and time are even more marked, and more widely recognized, in animals than in plants. Much current research in the dynamics of terrestrial animal populations is directed toward explaining these fluctuations and correlating them with climatic variables. Monitoring systems based on the animal populations of sample areas will necessarily have to take account of these normal, or at least unexplained, fluctuations.

Long term ecological trends may also mask changes due to a specific environmental modification. The forests of northern New Jersey are dominated overwhelmingly by oaks, and it is often assumed that this is the stable vegetation of the region. Buell et al (1966), however, believe that the area is generally capable of supporting mixed hardwoods and hemlock, and that normal ecological processes are presently leading toward development of such a forest. Two past influences, logging and fire, are probably responsible for the present oak dominance. The forests of the region were heavily cut and frequently burned, particularly in the middle of the last century. Oaks sprout vigorously after cutting or fire, and this apparently permitted them to gain an advantage over nonsprouting species. Wood cutting has decreased in recent years, and more intensive fire prevention efforts, coupled with greater discontinuity of forest units because intervening land has been converted to other uses, have made fires relatively rare. Maple, beech, basswood, and hemlock, formerly uncommon, are now able to perpetuate themselves and eventually to supersede the formerly dominant oaks. Rich mixed hardwood-hemlock forests are developing at lower altitudes, although oak-hickory forests may persist on the most exposed ridges (Buell et al 1966).

Ecologists and plant geographers generally consider the mixed hardwood forest of eastern U. S. to be characteristic of moister climates than oak-hickory. An ecological survey that detected a progressive shift toward sugar maple and associated species on sample plots at the expense of oaks could lead to the conclusion that greater moisture was creating the change in species composition unless the superimposed successional trend had first been identified and allowed for. Similar examples of current successional change could be cited from other regions likely to be exposed to weather modification.

Reconnaissance Surveys

Periodic reconnaissance surveys to detect changes in the organization of recognizable communities and to define shifts in their boundaries may be either an alternative or a supplement to repeated measurements on permanent plots. Many of the same difficulties that affect interpretation of sequential plot data will also appear in extensive surveys.

Changes in species distribution due to weather modification may be superimposed on changes due to other causes, known or unknown. Maps of the vegetation of the 145,000-acre Jornada Experimental Range in south central New Mexico have been constructed from available data for four dates: 1858, 1915, 1928, and 1963. These maps show a progressive increase in shrub abundance, and decrease in grass dominance, over the years. The changes are apparently correlated with heavy livestock use in the first 15 years of this century and moderate grazing since (Buffington and Herbel 1965). The area was designated as an experimental range in 1915, and since that time has received good management by prevailing standards. The specific reason for the vegetation change is not obvious, and this is important for the present analysis. The Jornada is in an area that might be chosen for weather modification, and as a federally controlled experiment station it could well be used as a site to monitor ecological effects of such a program. Clearly, it would be difficult to identify changes due to weather modification in this area that is already undergoing progressive change in vegetation cover.

Perhaps the most detailed reconnaissance yet undertaken to provide a baseline against which to measure ecological change was made in the Cape Thompson area of northwestern Alaska. At the time of the survey, it was proposed to construct a harbor on the Alaskan coast by nuclear excavation. This segment of arctic tundra is one of the last extensive areas on earth almost totally undisturbed by man. The Cape Thompson survey was an effort to determine the effect of a nuclear explosion on this environment -- its rock substrate, soils, atmosphere, and biota, including man. Data on all these phenomena were to serve as baselines for future assessment of change, either natural or man-caused.

The vegetation, almost uninfluenced by man's previous activities, was described and mapped in detail (Johnson et al 1966). The authors based their analysis on the concept that vegetation consists of discrete, continuous pieces rather than of continuous gradations. Vegetation types were identified and named when repeating patterns of vegetation association were found and when these patterns were associated with well-defined physiographic units. Eight major vegetation types were identified on the 38 square miles investigated in detail. These were broad categories that could have been subdivided into smaller units to fit other concepts of vegetation classification.

The important point for this discussion is that most of the vegetation types recognized in the survey blend with adjacent types; only a few types have abrupt boundaries. The width of the transition depends on the steepness of the environmental gradient. With this situation, there is no assurance that other workers, at other times, would draw the boundaries in precisely the same way even if equipped with the original investigators' field notes. In fact subconsciously they might tend to move them somewhat if influenced by the knowledge that a specific environmental change had occurred. Even here, in an area intensively investigated and almost free of extraneous interference, it is hard to see how repeated reconnaissance surveys could quantitatively define changes in plant populations or vegetation distribution of the sort likely to be brought about over a period of a relatively few years by weather modification. The same conclusion emerges from a review of the published reports on the animal (vertebrate and invertebrate) investigations carried out at Cape Thompson.

Remote Sensing

The emerging technology of remote sensing is likely to find a role in the reconnaissance aspect of monitoring programs. A capability for viewing earth surfaces at wavelengths extending across the spectrum from ultraviolet to microwave, combined with automated methods of image interpretation and information retrieval, may substantially extend application of remote sensing beyond what has previously been achieved with conventional aerial photography. A wide range of ecological applications of remote sensing is covered in a book edited by Johnson (In press). However, the resolution obtainable from most of the automated remote sensing data reduction procedures now available or in immediate prospect is probably insufficient to detect many of the subtle quantitative changes in plant and animal communities that give early warning of greater ecological changes to come. Individual interpretation of high quality aerial photographs is likely to fail for the same reason.

Remote sensing can, however, cheaply integrate those ecological characteristics of an extensive tract that define its spectral response — the so-called spectral signature. Spectral signatures change with time, as leaves develop in the spring and fade in the fall, for instance. Similar changes from year to year may be associated with accelerated growth of herbaceous vegetation or with increased moisture stress on overstory plants during the growing season. Many of these responses will be due only to normal weather variations, not to the long term shifts in total precipitation that might be produced by a weather modification program. Nevertheless, remote sensing could well be incorporated into the design of a monitoring system that compared the spectral signatures of a treated and untreated area over a period of years. A gradual shift in the average signature of the treated area unaccompanied by a similar shift in the signature of the untreated area might be due to ecological changes brought about by the weather modification program.

Because the shift could also be due to other natural or man-induced factors, such a comparison would involve statistical problems of the same sort as in other comparative studies. In addition, it is not now possible to relate shifts in spectral signatures directly to quantitative ecological changes. To put it crudely, we don't know just what kind of ecological response we are looking for on the ground, and even if we did we don't know how these changes would alter the spectral signatures detected by remote sensing. Nevertheless, investigation in this area should be pursued, in close collaboration with efforts to extend the use of remote sensing for other ecological and biological survey purposes. One illustration of how this might be done is a pilot project being undertaken by the Pacific Southwest Forest and Range Experiment Station, U. S. Forest Service, for detection of chronic air pollution injury to western conifers through remote sensing methods.

Indicator Species

Individual species of plants and animals differ in the sensitivity of their reactions to the environment. Especially sensitive species may disappear, or appear where they were formerly lacking, or change appreciably in abundance, as a consequence of deliberate weather modification sooner than similar effects can be recognized in the great mass of species. The use of indicator species would be especially attractive if enough were known to permit designating good indicators around which to build a monitoring program, but such is in general not the case.

The conspicuous or economically or esthetically important members of a community will seldom be the most useful indicators. For instance, oaks are important components of forest stands in northeastern United States. Concern has been growing since 1951 about extensive decline and death of oaks, particularly red oaks, in Pennsylvania. A 10-year study (Nichols 1968) showed that losses were highly non-uniform -- oaks were heavily affected in some localities and not at all in others. The primary cause of oak mortality was determined to be heavy defoliation by insects or by severe late spring frosts. Mortality ceased and recovery of declining oaks began when defoliation ceased, in spite of the longest drought on record.

It is entirely possible that weather modification, by subtly changing the environmental relations between insect populations and tree vigor, could either intensify or ameliorate the oak dieback problem (this is not a prediction -- merely an illustration). The observed past variability of oak mortality, however, is such that this important group would not be a good indicator of weather modification effects.

But could not some other major tree species that has not previously showed similar mortality serve? Probably not, because extensive tree mortality is usually a second order effect, brought about by increased populations of insects or fungal parasites invading already weakened trees.

What is needed is a species that responds rather directly to weather, but not so rapidly that population fluctuations reflect simply year to year weather. Annual grasses such as cheatgrass (*Bromus tectorum*) in western United States, for instance, differ markedly in growth from year to year depending on weather conditions. The mean height of mature cheatgrass plants is often a good indicator of the current year's growing weather, but within the rather wide climatic limits where cheatgrass is an important component of the vegetation, its size and abundance in any given year tell essentially nothing about long term climatic shifts.

More useful than plants as advance indicators of impending ecological change may be certain insects, particularly beetles and ants. Insects exceed all other terrestrial animals in both numbers of individuals and variety of species. They occupy a wide range of habitats and climates, and some species at least are very precisely adapted to their environment. Insects which show a well-marked preference for a particular environment should be valuable indicators of ecological change.

The ready mobility of many beetles, together with their high rate of reproduction, enable them to quickly colonize areas that become available during climatic change. There is evidence that well marked changes in beetle assemblages may be recognizable before a similar response is shown by the flora. The response of plants in a stable community to climatic change is strongly influenced by interspecific competition, but there is relatively little such competition among beetles (Coope 1967).

Species confined to a single host plant should not be selected as indicators. Nor do insects more or less independent of macroclimate, such as those that live in heaps of decaying refuse, make good indicators. The group of beetles that Coope (1967) has found most useful as climatic indicators in England are the Carabidae -- active ground beetles that have a wide variety of species, and being predators and scavengers, are not restricted to a particular source of food. Possibly they are more sensitive to temperature than to rainfall, however.

Non-colonial insects with highly efficient dispersal mechanisms are likely to be less suitable indicators of ecological change -- their distribution will mostly reflect year-to-year weather patterns. Occasional individuals of many species of grasshoppers and other insects are regularly found well above their normal limits in the Rocky Mountains. These accidentals are almost always species with well developed wings, whose dispersal depends on both flight and wind. Species with a high frequency of accidentals have an oscillating upper limit, advancing to higher altitudes in favorable seasons and being depressed to lower elevations in unfavorable years (Alexander 1964). Species with less efficient dispersal mechanisms, on the other hand, are likely to reflect mean conditions more than the weather of the year.

This suggests that ants may be among the best climatic indicators of all. As ground dwellers, the habitat preference of at least some species is apparently related to average soil moisture and soil temperature. An individual colony is long lived but not immortal. Dispersal is fairly effective but not so rapid as to be excessively influenced by current weather. The present distribution of ant species is rather well known, particularly in those parts of western United States likely to be early targets of weather modification.

Here as elsewhere, care must be used in interpreting observed changes in species abundance. There are many "tramp" species of ants which have been dispersed almost throughout the world, and which regularly displace native ants. Successive introductions may displace earlier ones at varying rates; this has obviously happened in Bermuda (Crowell 1968). If non-native ants are used as indicators, or if invaders are present, it must first be clearly established that there is some degree of stability in the ant fauna.

The ground-dwelling alkali bee is another interesting and economically important insect that may be a useful indicator of climatic change. Largely confined to clay soils in semiarid regions, alkali bees are valuable pollinators of native plants and of irrigated seed crops such as alfalfa. High soil moisture adversely affects survival and emergence of pupae by creating high humidity in the pupal cells, which in turn encourages germination and growth of deleterious fungi (Stephen 1965). Alkali bees are quite finely adjusted to the soil environment, and an appreciable change is likely to be reflected by bee populations. They are somewhat slow to colonize new habitats, however, and therefore may not be good indicators of newly favorable conditions.

Only suggestive possibilities have been indicated here. A survey of the entomological literature should be carried out to define suitable insect indicators of impending ecological change. Substantial field work is likewise required. It appears that such research could result in a valuable means for signalling prospective biological change.

Phenology

Phenology -- the relation between climate and recurrent biological phenomena such as bud opening, flowering, bird migration, and the like -- may also offer promise as an ecological indicator. The potential of plant phenology as a microclimatic surveillance tool has recently been reviewed by Wang (1968). He suggested the following criteria for selecting indicators of phenological events: (1) the organs involved must be sensitive to environmental variations; (2) the time variability of an event in the field should not be more than a day or two; (3) the indicator must permit objective determination of the timing of an event, reproducible among observers; (4) the method of determination should be simple and easy to execute.

An extensive but largely uncollated body of phenological data has accumulated, much of it contributed by amateur observers. The Phenology Project of the International Biological Program is designed to analyze and extend these observations. Phenology has to date been related to temperature and day length much more than to precipitation. It is not at all certain that identifiable phenological changes will be associated with a weather modification program, but the possibility should be investigated. It is likely that remote sensing methods will be particularly useful in phenology studies.

STATISTICAL ANALYSIS AND EXPERIMENTAL DESIGN

An experimental design upon which some proposals for weather modification monitoring are implicitly based is the paired comparison method often used to determine the effect of management practices on water supply. Two or more adjacent catchments as nearly alike as possible in area, vegetation, soils, geology, and other physical factors are selected, and gauging structures are placed at the outlets of each. After several years' data on such hydrologic characteristics as total yield, flood crests, and sediment load have accumulated, a regression equation is developed to estimate the flow of one catchment from the measured flow of another. This makes it possible to account for streamflow variations caused by year-to-year differences in precipitation, temperature, and other factors not associated with the proposed treatment. A treatment, such as removal of all trees, is then applied to one of the catchments. The regression equation is used to predict, from the measured flow of the other basin, what the flow from the first would have been in the absence of treatment. The difference between the observed and the predicted behavior is assumed to be the result of the treatment.

The paired comparison design assumes that the two areas in their unmodified condition respond alike to weather. This is assured as far as possible by choosing catchments similar in soils, slope, exposure, and prior treatment. The design also assumes that the two members of the pair are exposed to nearly the same weather after treatment. To this end, the paired catchments are normally adjacent to one another, and are kept small. Thirty to 50 acres is a common size.

The greater the variability of the dependent variable (runoff from the basin planned for treatment) around the regression line during the pre-treatment period, and the smaller the effect of the treatment, the longer both the calibration and the post-treatment testing periods must be (Cooper 1963). Even under the best of conditions, three or four years of calibration and an equal post-treatment observation period are necessary to evaluate the statistical significance of a change in runoff brought about by a drastic alteration of watershed vegetation. If the regression between the two basins is quite variable, or if the treatment is relatively modest, much longer may be necessary. There is some tradeoff between length of calibration period and length of post-treatment observation period, but an irreducible number of pre-treatment calibration years is always required.

The nature of storm systems and of weather modification technology will compel treated and control areas to be separated by a much greater distance than is necessary in watershed comparisons. Hence the pre-treatment calibration relations are almost certain to exhibit considerable variability about any plotted regression line because the two areas will be exposed to different weather. With present knowledge, this can only in part be compensated by incorporating temperature, precipitation, and other weather variables into the regression. Plant and animal populations are likely to be more variable in response to normal and modified weather than are water flow and other hydrologic variables. Long calibration and post-treatment observation periods will therefore be required.

Hydrologic evaluation has occasionally been attempted without prior calibration by after-the-fact comparison of one or more treated basins with untreated catchments that are assumed to be suitable controls. There is no effective way of knowing in these circumstances how much of the observed difference in hydrologic behavior is due to the treatment and how much to inherent differences in catchment characteristics. There are so many sources of bias in comparisons of uncalibrated catchments that such comparisons normally show only the direction of trends. Except under highly favorable circumstances, quantitative estimates that will stand up to statistical scrutiny cannot be made by this method (Cooper 1963). The same is true of programs to evaluate the ecological effects of weather modification. It will be almost impossible to draw truly meaningful conclusions without an adequate pre-treatment calibration period.

Other proposals for monitoring surveys do not involve comparison with a control area. In such a design, the area subjected to weather modification is examined before and after treatment. The implied assumption underlying this design is that vegetation and animal communities are essentially static in the absence of a specific environmental change. Divergences from the pre-treatment condition can therefore be attributed to the weather modification alone. However, normal ecological processes could also have been responsible for the shift, or other environmental alterations may have intervened.

A final problem in design for statistical evaluation of weather modification effects is the length of time that will normally be required for these effects to become manifest. Mature perennial plants are apt to live for years after conditions have become unfavorable for their reproduction. New species, growing slowly, may require many years to become dominant. Proper interpretation of changes in age structure and of seedling populations, however, may provide significant warning of more obvious changes to come.

ENVIRONMENTAL BASELINE STUDIES

Despite the reservations expressed about the difficulty of measuring some of the direct effects of weather modification in a short period of time, it is important that a start be made immediately on a network of monitoring stations to evaluate measurable ecological changes due to natural factors and to all forms of human technology, including weather modification. Pertinent suggestions to this end have come from many sources, but many of the recommendations in the following section of this report are due to Dr. Bengt Lundholm of the Swedish Natural Research Council, Stockholm.

The Swedish group has proposed erection of a global network of baseline stations devoted to monitoring biotic and abiotic factors in the environment. The purpose is to provide a means of assessing short term and long term changes brought about by a variety of factors, including many forms of pollution. It is anticipated that this network will be closely tied in its formative period to the research activities of the International Biological Program.

We urge that agencies sponsoring research and development in weather modification initially contribute a substantial share to the planning budget for such a monitoring network, and to the operating costs of the United States portion after its establishment.

What Should Be Measured?

The following examples are given to suggest important elements of a program, and are not intended as definitive suggestions. Emphasis is given to those characteristics that are apt to be most closely related to weather modification.

1. Climatic parameters, including not only standard meteorological measurements but also insolation, atmospheric turbidity, and the like.

2. Composition of abiotic materials. Chemical analyses of air, water, and soil should be made regularly. In air, for example, the levels of oxygen and carbon dioxide should be followed, as well as the levels of selected pollutants. Chemical composition of rainwater should be monitored. Special attention should be paid to silver, iodine, and organic compounds used as artificial nucleating agents.

3. Chemical composition of organisms. This aspect has to do mostly with accumulation of pollutants, including organic compounds and heavy metals. Although of crucial importance to the overall value of a monitoring network, this aspect is less relevant to weather modification, except possibly with respect to silver.

4. Biological parameters. Some of the possible biological indicators of weather modification have been mentioned in previous sections. In addition, the relation of small rodents to their environment may be evaluated by their abundance and perhaps by such metabolic factors as respiratory quotient. Many species of small birds are near the tops of the food chains and are thus very sensitive to changes in ecosystems. They are also relatively easy to census. Evaluation of the population dynamics of small birds may be very useful in assessing effects of environmental change. Environmental changes affect the activities and numbers of microorganisms which decompose cellulose or fix nitrogen. Methods that record differences in activity, number, or physiology of micro-

organisms are worth consideration. The possible utility of indexes of diversity and abundance of selected insect groups has already been referred to. Two other types of biological response to weather modification are likely to be of sufficient importance in a monitoring system that they are discussed separately.

Tree Rings as Calibration Devices

A principal difficulty in monitoring, as already noted, is the relatively long pretreatment period needed if statistical analysis is to identify some of the rather subtle but possibly pervasive and long lasting effects of weather modification. Year to year variations in width of annual rings integrate virtually all of the environmental factors impinging on a tree. To the extent that tree ring sequences reflect weather regimes of the past rather than other environmental variables, they provide almost the only long-lived indicator of past conditions with which the present situation can be compared. Although there are many problems yet to be solved, tree ring analysis may be an important aid to ecological monitoring.

The basic concept is the evaluation of rings laid down by selected trees before and after the start of a weather modification program. Standardized methods are available for removing trend lines due to changing patterns of growth as the trees mature (Fritts 1969). Increment cores might be extracted from sample trees perhaps 5 to 6 years after the weather modification program begins. Ring sequences before and after the starting date would be analyzed. Significant differences in mean ring width in the two periods might be due to the effects of weather modification or to other causes. There is a twofold interpretation problem: it is not evident how much of any observed effect is due to weather modification rather than to other environmental factors, and ring variations do not themselves measure other important biological responses. Nevertheless, tree rings may be one of the best calibration tools available where an extended pretreatment sampling period is not allowed. Additional research is needed to better define the relation of tree ring width to climatic variables in regions likely to be subject to weather modification, and to translate ring width variations into identifiable responses of animals and other plants.

Vegetation Responses on Sample Plots

It is important that steps be taken immediately to develop and test standardized procedures for measuring responses of plant communities to weather modification and other environmental change. Two vegetation types seem particularly suitable for initial tests: a rangeland area with about 20 inches annual precipitation, and possibly a mountain grassland site. These areas are likely to be relatively sensitive to weather modification, and biological changes will be easier to detect than in some other vegetation types. If the feasibility of a field monitoring program can be established here, tests can be extended to more difficult localities. A tentative outline of how such measurements might be made in a range area is presented below:

Physically the treated and control sampling areas should be:
- Under the same isohyet (where mapping is at two-inch differences in mean annual precipitation).
- On comparable soils.
- No more than about 70 miles apart.
- Uplands, essentially on a plain with no more than about a 400 foot difference in altitude.

Vegetationally the treated and control rangeland areas should be:
- Stable -- vegetation development in equilibrium with soil.
- Ungrazed by domestic livestock and unmowed for at least three years.
- Each sampling area to be not less than one acre in extent. Sampling areas, and plots within samples, to be replicated as indicated by statistical design.
- Fenced and protected from livestock grazing and mowing through the term of the research. (Funds permitting, a small rodent exclosure to be included within each livestock exclosure.)

Sampling of any vegetation change due to weather modification to be:
- By comparison of vegetation measurements through time in the treated and untreated sampling areas.
- By a method (1) producing least possible disturbance in natural perennial herbaceous vegetation that will have to be remeasured periodically; and (2) that is least affected by normal fluctuations in seasonality of growth and normal year to year fluctuations in total annual herbage yield.
- From several small livestock exclosures in both treated and control areas. The exclosures to be spaced at one-half mile or greater intervals to permit properly evaluating effects of rare but quite local "cloud bursts" and great hail storms in the narrow tracks of summer thunder storms.

There are five principal ways of expressing quantitative relations in rangeland vegetation. They are:

a. Production -- weight of plant matter produced per unit of area annually, or in some other unit of time.
   Production may be measured as oven-dry weight of aboveground growth of plant tissue, in grams per meter square or pounds per acre, per year. Production by a given species can be expressed either in these absolute amounts,

or as relative production, e.g., 30% little bluestem production out of the total production by all species.

b. Biomass -- weight of plant matter present at a given time. In grasslands, biomass may be determined by clipping and dry-weighing above-ground plant matter, and may be expressed as either absolute or relative quantities. Biomass is more easily determined, but less effective as an expression of community function, than production. In both cases measurements on roots are desirable in theory, but may not be necessary in practice.

c. Coverage -- the fraction of the ground surface which plants occupy, or which the projections of their foliage to the ground surface would occupy. Coverage is termed basal coverage when stems are measured near the ground line. It is termed foliar coverage when based on projection to the ground of foliage cover at full annual growth. Either basal or foliar coverage can be expressed in absolute or relative amounts.

d. Frequency -- the fraction of small sample plots taken within a given community in which a given species occurs. The importance of a given species is expressed by the percentage of sample small plots (generally one meter square or less) in which the species occurred. Individuals are neither counted or measured. Species are recorded, in each plot examined, simply as present or absent. A species that occurred in 50 out of 100 equally or randomly spaced plots could be reported as having a frequency of 50%.

e. Population density per unit of area. All the specimens of each species in a plot are counted but not measured. The importance of a given species is presumed to be expressed by number of individuals per unit area (and by relative density -- a given species' percentage of all individuals of all the species recorded in the sample plot).

Each of these measures -- production, biomass, coverage, frequency, and density -- may be summed for all species to produce a community-level measurement of interest. A further community-level measurement of significance is species-diversity or richness in species, which may be approached through numbers of species in sample plots, and through certain measurements based on relative importance of species.

We suggest that measurements to study effects of weather modification on rangeland should be concentrated on (but not necessarily limited to) basal coverages, expressed as percentages of the total basal coverage by perennial species, and as total community basal coverage.

For this purpose we suggest line-interception transects. The lines would be used as permanent lines for sampling between iron stakes through time instead of for sampling vegetation over space. Iron stakes driven about 18 inches into the ground 20 or 25 feet apart would constitute a sampling unit or plot. A strong thin string (60 lb. test nylon fishing line) is stretched between stakes when basal area is read and then removed until the next reading. Significant changes in percentages of basal coverage by native perennial grasses generally require a minimum of two years. Therefore, rereading of lines at two-year intervals is suggested.

The LaPorte Anomaly

The so-called "LaPorte Anomaly" offers a possible test case in evaluating ecological effects of an assumed weather change, but one that is made more difficult by lack of prior calibration. Precipitation in the area around LaPorte, Indiana, has apparently been substantially increased since about 1925 as a result of nucleation by smoke from the Chicago-Gary industrial complex some 30 miles upwind (Changnon 1968). The postulated increase amounts to 30% or more during the warm season of the year.

In the course of a survey of natural areas in Indiana, one of the few relatively undisturbed forest stands within the high precipitation area was sampled by Prof. A. A. Lindsey of Purdue University before he had heard of the apparent anomaly (personal communication). The sampling crew were surprised at the large average size of the trees in the stand, and Prof. Lindsey's field notes remark that the shrub layer was unusually profuse. There is, of course, no information on conditions before 1925. Plant and animal responses different from those in adjacent areas of "normal" precipitation could be due to a variety of causes: Temperature differences (north or south of LaPorte), preexisting precipitation differences (east or west), air pollution, time since introduction of damaging organisms (Dutch elm disease) and a host of others.

Despite these problems, we recommend that a relatively brief and inexpensive preliminary ecological survey of the LaPorte area be undertaken as soon as possible. Plant and animal populations in remnant forest stands and in agricultural and park lands should be compared with those in similar areas immediately outside the anomaly. If the preliminary survey reveals apparent significant differences in any of the measured characteristics, a more intensive investigation should be mounted.

X. INFERENCES FROM ECOLOGICAL THEORY

Ecological theory, incomplete though it still is, leads to broad predictions about the types of responses to be expected from most ecosystems exposed to weather modification, the relative rapidity or sensitivity of their response, and the effectiveness of biological mechanisms resisting change. In arguing from ecological theory, as opposed to empirical observational evidence, several points must be considered: (1) Plants and animals in competition respond to environmental variables differently than when tested alone; (2) The distribution of plants and animals along an environmental gradient is not a simple response to climatic and soil factors, but involves second and higher order interactions; (3) Weather modification is likely to be only one of several management techniques used by man in a given area; other cultural practices and inadvertent climatic change may intensify or counteract the effect of weather modification; (4) Weather modification is a change imposed on an already variable environment.

IMPACT OF MULTIPLE STRESSES

The fact that weather modification is only one of many simultaneous changes imposed by man complicates the ecological response. There are grounds for concern that weather modification, when combined with the whole range of other environmental stresses that are becoming increasingly pervasive, may lead to unanticipated cumulative effects.

Several stresses, each small enough to be relatively insignificant when acting alone, may be more effective in concert than a single stronger stress. Suggestive evidence comes from computer models of bacterial cell synthesis. Simulated experiments in which a single large stress was compared with three or more small stresses led Yeisley and Pollard (1964) to report that ". . . we were surprised to find that simultaneous stresses are more effective than greater single stresses." There is no proof that this is in general true of ecosystems in the real world, but the point should be investigated further. It may be that weather modification in combination with, say, atmospheric pollution will have a much greater effect on plant and animal communities than either alone.

INDIVIDUAL VS. COMMUNITY RESPONSE

Few features of semiarid and mountainous regions are more marked than the differentiation of plant cover into distinctive community types which replace each other along gradients of moisture, temperature, and other environmental variables. Associated with each recognizable vegetation type is a distinctive aggregation of birds, mammals, insects, and other animal groups. Yet it has been shown convincingly in recent years that vegetation may be interpreted as a largely continuous population (McIntosh 1967; Whittaker 1967b). Each species has its own range of tolerance to temperature, moisture stress, and other environmental variables; their densities taper off on each side of the population optima. Each species has its own optimum, although some may nearly coincide. Because of the scattered distribution of species optima along the environmental gradient, species form a population continuum. Dominant plants may provide a favorable environment for subordinate vegetation and for animals, leading to recognizable communities which apparently give way to each other along the gradient.

Nevertheless, the dominant plants respond to a multi-dimensional gradient, of which moisture is only one aspect, and their response to this gradient depends in part on interspecific competition. Ellenberg's (1952) classic study of the role of interspecific competition in regulating responses to environmental variables showed that the optimum environment for a grass species grown in a pure stand was not the same as when the species was grown in competition with other grasses. Furthermore, the optimal moisture level for a given species depended upon the particular associates planted with it.

This is apparently true for natural vegetation as well. For example, the composition of the dominant plant associations in the northern Rocky Mountains largely reflects the local climate. The particular grouping observed at any point in this region is the outcome in a given climate of intense competition among vascular plants with different reproductive abilities. There is no assurance that these associations would uniformly replace one another if one major climatic variable such as precipitation were changed while the others were held constant (Daubenmire 1952).

This reasoning can be made more general. At any one time the population size of each species in an ecosystem is the result of a complex network of interacting factors, some intrinsic to the organism and some externally controlled. Therefore, even if it were possible to determine the exact physiological response of . isolated individual or species population to a particular weather change, this would not necessarily establish whether the species will increase or decrease in an actual ecosystem as a result of the weather change. Since a change of rainfall will not affect all species alike, there will not be a uniform replacement of one biological community by another under the influence of artificially augmented precipitation. Rather, at least some plants and animals will become regularly associated with species among which it would previously have been surprising to find them.

Adjustment of Plant Communities to New Moisture Levels

It is axiomatic that physiological responses to additional moisture will be important only if there is some alleviation of moisture stress. The additional rain need not fall during the stress period; prolongation of soil moisture availability in the spring by augmenting winter carryover storage in the soil or in the snowpack can also avert water shortage.

Where available water is the major limiting factor in plant distribution, species seem to be governed at the lower limit of their tolerance chiefly by inability to secure enough moisture for survival at some critical stage in their life history. At the upper level of the moisture range within which a species can thrive in nature, the controlling factor is evidently competition with more aggressive species having higher requirements for available moisture. An increase in mean rainfall may bring about biological change through several mechanisms: (1) invasion of new species with moisture requirements too high to have been satisfied previously; (2) elimination of species that had formerly maintained themselves under a moisture regime within their range of tolerance but wetter than their optima; and (3) changes in abundance of species already present for which conditions are either more or less suitable than formerly. The last is likely to be most important.

Changes in dominance will result because aggressive species previously limited in their growth or reproduction by inability to obtain enough moisture at some critical stage in their life cycle are now able to do so. Decreases in abundance of other species will seldom be due to physiological excess of water (except if soil waterlogging occurs, but deliberate rainfall increase will rarely be attempted where this is probable). Rather, such decreases are likely to occur as a consequence of competition from species already present in the area, but held to less than maximum growth levels by suboptimal moisture. With added moisture available, these species can grow more vigorously, depriving their less favored competitors of nutrients, sunlight, or other requisites for survival. Completely new invaders may also appear, possibly in spectacular numbers, but the invaders are likely to be still sufficiently close to the margin of their existence that they cannot compete aggressively enough to drive out existing species without help from species already present on the site.

WEATHER MODIFICATION AND CLIMATIC VARIABILITY

Weather modification is a change imposed on an already variable environment. Natural changes of at least the magnitude expected from planned weather modification have characterized temperate climates for millenia. It will not be easy in the short run to distinguish ecological change due to deliberate weather modification from those induced by simultaneous natural climatic variation.

This statement should not be confused, however, with the frequently-stated fallacy that because the normal variability of weather is about as great as the change expected from weather modification, the latter will have no biological effect. The argument developed throughout this survey of ecological effects of weather modification is that plant and animal communities respond in the long run to mean climatic conditions, not to isolated events. Weather modification designed to increase precipitation will, if successful, by definition alter mean rainfall. Plant and animal communities must eventually adjust to the new conditions. The length of time required for such adjustment may, however, depend upon the variability of the pre-modification rainfall regime.

The hypothesis is that areas subject to great year-to-year variation in weather will be less susceptible to a planned change in precipitation than areas of comparable but more uniform weather. As Gleason (1939) put it, "The rare disappearance of a species because of environmental fluctuations is probably due to the fact that the fluctuations of any one year have been repeated at various times in the past, and species which would have been exterminated by them have already been removed." If, however, a new climatic situation is introduced in which organisms frequently encounter conditions that they have not been accustomed to meeting, biological change is likely. Organisms will encounter such conditions more frequently as a consequence of a quantitative increase in mean annual rainfall if the previous mean had a low standard deviation associated with it thanif the normal rainfall variability was great. This assumes that weather modification changes the precipitation mean without altering its variance. It would not necessarily apply if the modification program exaggerated the high precipitation events.

The argument applies with equal vigor to invasions of moisture demanding species. If a plant can germinate and become established during occasional years of above-normal precipitation, it can often persist for many years as a regular component of the vegetation. If year-to-year rainfall is highly variable, abnormally wet years will be frequent enough to encourage this process, whereas if the rainfall pattern is normally quite uniform, such abnormally wet years will be rare. Thus when mean annual rainfall is increased, moisture episodes not previously experienced will be quite rare in the high variability areas. The principal change will be that conditions for invasion will be favorable more often than formerly. In the low variability areas, however, an appreciable fraction of the wettest years after weather modification may be wetter than any years previously experienced during the lifetime of the plants and animals now occupying the site. As stated by Janzen (1967), greater sensitivity to change is promoted by less frequent contact with that change.

A corollary to the preceding is that communities displaying wide year-to-year fluctuations in the populations of their components will be less sensitive to climatic change than those with stable populations. Wide population swings are typically associated with relatively simple communities, as in the arctic and the desert, which encounter great annual variations in environmental conditions. Many of the species present are adapted to take full advantage of favorable conditions, and to ride out unfavorable years at low population levels. A change in mean annual rainfall would be likely to change the ratio of favorable to unfavorable years, but not to eliminate either entirely.

SENSITIVITY TO CHANGE IN RELATION TO CLIMATE AND SOIL

The biological change produced by a given percentage increase or decrease in precipitation will be least in humid climates, greatest in semiarid, and somewhat less in arid regions. This of course is a broad generalization, and assumes that all other conditions are essentially equal.

Ten percent more rain in a region already abundantly supplied will mostly run off. The growth of plants in such a region is limited by the supply of solar energy more than by availability of moisture. Plants in a humid climate which fail to become established despite the availability of a seed supply are usually limited more by lack of light or essential nutrients at a crucial stage than by moisture. Species for which conditions are currently unfavorable will therefore not usually be significantly aided by additional moisture.

In a semiarid region, by contrast, much of the added precipitation will be captured by plant roots and carried into the transpiration stream. The plants exist under a moisture deficit during much of the year; even a small reduction in the deficit may permit a species to thrive where it had formerly been excluded. Therefore, a 10% precipitation increment in a semiarid region, although this would be a smaller absolute increase than a similar proportional increment in a humid region, may nevertheless bring about a greater biological change.

In a truly arid region, however, the absolute increment from a similar proportional change is small in relation to the enormous moisture deficit. Observations of patterns of desert vegetation in response to climatic gradients suggest that the effects of weather modification will mostly be limited to some increase in growth and flowering of annual herbs, such as now occurs in years of above normal rainfall; and some increase in growth rate, and eventually in coverage and density, of the shrubs which now dominate desert communities, but without major change in species composition.

Soil Depth

Plant communities on deep soil with high water holding capacity are likely to be less affected by weather modification than adjacent communities on shallow soils. This hypothesis was suggested by computer simulation experiments now in progress at The University of Michigan. Soil of higher water holding capacity is better able to buffer the effects of periodic moisture stress, so that the plant response is governed by the yearly average rainfall rather than by short term fluctuations. Practically all rainfall is stored in areas of deep soil in semiarid regions, whereas much rain on shallow soil may run off after the small storage capacity is satisfied.

These conclusions are supported by contrast in vegetation structure on opposite slopes in the chaparral region of Arizona (Saunier and Wagle 1967). The abundance of shrub live oak *(Quercus turbinella)* was measured on dry south-facing slopes and on moister north-facing slopes on each of three soil types. One soil, derived from quartz diorite, was a relatively shallow sandy loam but with considerable available water storage per unit of depth and with a highly fractured and decomposed substratum that provided excellent avenues for penetration of both roots and moisture. The other soils, derived from sedimentary and volcanic formations, were slightly deeper but had lower water holding capacity per unit of depth and had an impermeable substratum.

There was a several-fold difference in abundance of oaks on north- and south-facing slopes derived from the last two substrates, with many more plants on the protected north slopes. There was essentially no difference between slopes in abundance of oaks on quartz diorite; the south-facing slope on this substrate had as many oaks as the north-facing slopes on the other two soils. These results can be interpreted to mean than a modest increase in precipitation would affect the vegetation on the sediments and volcanics more than on the quartz diorite (provided of course that infiltration conditions are similar in all cases). Contrasting slopes in this part of Arizona have sharply different local climates. Despite the climatic difference, the plants on quartz diorite were equally abundant on both slopes, presumably because of a greater supply of available water during critical periods.

EFFECT OF COMMUNITY DISTURBANCE AND ECOLOGICAL SUCCESSION ON SENSITIVITY

A substantial change in the structure of uncultivated ecosystems as a result of weather modification is more likely under conditions of moderate disturbance than in either an essentially undisturbed climax community or in an area continually disrupted by man or by natural catastrophe.

Evidence has already been presented that changes are more likely in moderately grazed midcontinent grasslands than in either ungrazed or severely grazed areas. The effects of very heavy grazing or similar continuous disturbance are similar to those of agricultural land preparation and cultivation: species not able to tolerate the disturbance are eliminated, and others, unable to compete in nature, thrive. The difference in economic consequences of the two processes obscures their ecological similarity. The principal difference is that in agriculture the favored crop is chosen; in overgrazing it is not. Just as agriculture can permit a crop to be grown under a wider range of climatic conditions than in nature, severe and continuous disturbance will generally permit only those species adapted to the disturbance to persist, and to do so over a fairly wide climatic range. A moderate increase in precipitation under these circumstances is likely to stimulate growth of disturbance-adapted species, but not to alter species composition greatly.

On the other hand, a moderate increase in precipitation may not greatly change an essentially closed climax community even over several generations. Natural biomes have a well-established, stable animal-soil-vegetation complex which is not delicately balanced. A moderate man-induced environmental change does not normally set off a dramatic chain reaction of responses unless that change is accompanied by introduction of alien animals or plants, farming, grazing, logging, man's use of fire, or natural catastrophe (Howard 1965).

Suggestive evidence is provided by two experiments in which artificial fertilizer was applied to adjacent plots of native and disturbed grassland: one in the midgrass prairie of Oklahoma (Huffine and Elder 1960); the other in the shortgrass region of northeastern Wyoming (Cosper et al 1967). In drawing an analogy from these experiments to precipitation increase, it is assumed that the nature of the response to alleviation of a limiting factor will be roughly the same regardless of whether that factor is soil moisture or soil nutrients.

In the Oklahoma experiment, ammonium nitrate and superphosphate were applied to native pasture that had never been plowed but had been heavily grazed in the past, and to abandoned and eroded cropland on which native grasses had been allowed to reestablish themselves naturally over some 20 years. Both areas had been grazed more or less continuously before fertilizer aplication, but not during the period of measurement.

Fertilizer treatment had less effect on the botanical composition of the unplowed grassland than on the abandoned cropland. Annual weeds were substantially increased by fertilization on both areas, but the proportional increase in weed growth was much greater on the cropland plots that had supported only a poor stand of native grasses.

In the Wyoming experiment, a single application of nitrogen fertilizer to deteriorated range dominated by weedy forbs changed the botanical composition to a mixture of western wheatgrass and shortgrasses. The same amount of nitrogen, applied to a similar soil on which native shortgrass species represented 80% of the total vegetation, did not appreciably alter botanical composition. Total yield was substantially increased by the fertilizer on both sites.

In both the Oklahoma and Wyoming experiments, all plots were protected from grazing for the duration of the study. They were thus able to change appreciably in botanical composition as a result of the treatment. It is likely that heavy grazing of the deteriorated vegetation would have removed most of the newly favored species as they appeared, holding species composition nearly where it had been before treatment.

In another part of the world, seeds and transplants of *Rumex crispus* and *R. obtusifolius* introduced into various closed grassland and woodland habitats in Britain failed in every instance to establish themselves as a part of the community (Cavers and Harper 1967), even though they are normally found in such habitats. Seedlings arose from the planted seed but failed to survive; transplants persisted longer than seedlings but gradually lost weight and died. The authors attributed the present natural occurrence of these species to past physical disturbance. Much similar evidence can be cited for the difficulty of establishing new species in closed communities, and for consequent relative insensitivity of such communities to environmental change.

Some community dominants and subdominants such as aspen *(Populus tremuloides)* in cool temperate forests and *Agave lechequilla* in the southwestern Chihuahuan Desert form extensive clones in which reproduction is almost wholly vegetative. Inefficient dispersal mechanisms tend to slow the spread of such species into new habitats made available by weather modification. On the other hand, their vegetative habit makes them resistant to displacement by other species for which weather modification might create more favorable conditions.

A hypothesis related to successional status is that the groups of organisms in a given area likely to be least sensitive to weather modification are those which pass the first part of their life in microclimates more uniform than the regional macroclimate. Such microclimatic uniformity is more likely in fully developed forests and grasslands than in open successional or disturbed vegetation, and on shaded north slopes than on south-facing exposures. Thus, Aubreville (see King 1953) believes that many forest formations in tropical Africa are paleoclimaxes imperfectly adjusted to the present climate. The vegetation had its origin in an environment more moist than that of today. The forest microclimate creates local conditions that permit regeneration of forest species in regional climates that would otherwise make this impossible. Aubreville believes many tropical forests to be highly unstable and susceptible to change under human influence. If his hypothesis about widespread drying of the African climate is correct, precipitation increase through seeding of tropical cumulus clouds could increase the stability of some African forest communities.

The revegetation of essentially bare soil, particularly in semiarid regions, generally follows a fairly consistent path regardless of differences in weather. Succession on newly cleared ground in southern Idaho from which all grazing mammals, wild and domestic, are excluded follows an almost invariable sequence: two years of Russian thistle *(Salsola kali)*, two years of annual Cruciferae, with cheatgrass *(Bromus tectorum)* dominant thereafter. This pattern occurs in wet and dry years. The time required may vary if moderate grazing periodically removes developing vegetation, but the sequence is consistent (Piemeisel 1951). These early stages of succession are unlikely to be much altered by precipitation changes of the magnitude contemplated in weather modification.

MECHANISMS OPPOSING CHANGE

Compensatory mechanisms may sometimes interact to limit the biological change resulting from weather modification. For example, it is generally accepted that low average temperatures and short growing seasons are the principal climatic factors restricting growth of pine and spruce in Finland. Yet Mikola (1952) found that these species did not grow any faster during the period of high temperatures and long growing seasons in the 1930's than during the period 1910-1930. This he attributed to the damage caused by noxious insects which were known to have been favored by the mild winters during the warm period. It is conceivable that the stimulus to forest growth of increased precipitation might be balanced by greater insect activity.

Territorial behavior may also damp the effects of weather modification on animal populations. The size of defended territory places an effective upper limit on the size of a breeding population. In species showing territorial behavior, there is seldom the tremendous variability in numbers from year to year that characterizes some other animals (Etkin 1964). Strongly territorial birds and mammals would thus be poor indicators in an ecological monitoring program. It is not yet established, but the same may be true of those desert plants that seem to show territorial behavior through release of chemicals that inhibit nearby competitors.

POSITIVE FEEDBACK THROUGH CHANGES IN SURFACE CONDITIONS

What of the possibility that artificial increase or decrease of precipitation could so upset a delicately balanced local climate that additional changes are self-generated? Mechanisms can be visualized by which this might happen.

Let us first dispose of the idea that additional precipitation, by making more water available for transpiration, would increase local humidity and so increase rainfall still more. If true, this would indeed be a remarkable bootstrap operation. A moment's reflection will show that causing precipitation to fall artificially must reduce the water content of the atmosphere by more than the amount subsequently added by transpiration, if there is any runoff to the ocean. More fundamentally, McDonald (1960) has persuasively argued that deficient precipitation, even over deserts, is almost never due to lack of atmospheric moisture, but to lack of an adequate cooling mechanism to induce condensation, and occasionally to lack of sufficient condensation nuclei.

Neither does it appear that alterations in surface characteristics as a consequence of vegetation changes brought about by weather modification will affect the energy balance and convective air currents enough to change local precipitation patterns. There is evidence, however, that human activity, by reducing vegetative cover and increasing atmospheric dust, has set in train a process that has decreased precipitation over the Rajputana Desert of northwest India and adjacent Pakistan (Bryson and Baerreis 1967). The reduction in precipitation has in turn led to more depletion of vegetation, more dust, and so on in a process that feeds on itself.

According to this hypothesis, elimination of airborne dust through increase in soil-stabilizing vegetation could change radiative cooling processes in the atmosphere enough to reduce subsidence, or mean rate of downward air movement, by about one-third. Assuming that the variance of vertical air movement is not changed in the process, shifting the mean nearer zero would result in more instances when the vertical component was actually directed upward. Summer showers in deserts like the Rajputana are usually associated with the relatively infrequent occurrence of upward air motion, so that decreased subsidence could lead to more frequent showers. In addition, more solar energy would reach the ground if dust were reduced, and there would be less heating of the upper air by radiation absorption in the mid-troposphere. Both factors would lead to greater daytime atmospheric instability, which could also bring more rain. More summer showers would aid the grass which in turn would hold down the dust still more, and so on.

Bryson and Baerreis suggested that the initial improvement in ground cover might be achieved by temporarily restricting livestock grazing. It is doubtful that similar results could be achieved, there or elsewhere, by artificial cloud seeding, because cloud seeding would not be effective unless atmospheric conditions were first changed through reduction of dust, and even if it were, additional rain would not much reduce the dust without concurrent control of grazing. Furthermore, only where atmospheric dust is a major climatic factor would this kind of self-accelerating change occur, and there are few desert regions where dust is as important as in the Rajputana.

It is significant that in the area around Phoenix, Arizona, where dust was never particularly conspicuous, a careful analysis (Anderson 1936) failed to show evidence of a change in precipitation following large scale development of irrigation, even though irrigation increased transpiration and altered the surface energy balance by replacing sparse desert vegetation with dense agricultural crops. There seems little reason to believe that vegetation improvement through weather modification will have beneficial feedback effects on climate in most parts of the world.

SPECIES EXTINCTION

Mammals

Large mammals, at least in North America, are unlikely to be rendered extinct even locally as a consequence of weather modification. Large mammals continue to exist now only by sufferance or active intervention by man, through regulation of hunting and manipulation of the habitat. The change to be expected from anticipated kinds of weather modification is small enough, and wildlife management techniques well enough developed, that big game species could be maintained, except possibly if increased snow eliminates an already critically short winter range. The esthetic value of these large mammals might be reduced by increasingly artificial maintenance of their populations, but a long step in this direction has already been taken in the U. S.

The public is less interested in small mammals, which would largely have to fend for themselves. All the 64 genera of small mammals (excluding bats) recorded as fossils in North America since the start of the Wisconsin glacial advance survive today except for the giant beaver *(Castoroides)*. This despite changes in climate far in excess of anything expected from weather modification -- changes which, along with the activities of primitive man, contributed to the extinction of at least 30 percent of the contemporary larger mammal species (Axelrod 1967). Small mammals live in protected dens or burrows, commonly store food, and mate in spring so the young start life at a favorable time. A few birds, like the Kirtland warbler, and perhaps some mammals, are completely dependent on a particular species or stage of vegetation. Where this is the case, the host plant is usually fairly widespread. I know of no North American vertebrate likely to be rendered extinct because weather modification will totally destroy its habitat. Changes in abundance are to be expected, however.

Plants

There are several categories of rare plants which might be subject to extinction: (1) those that are (and may always have been) adapted to unusual, very local, soil or geologic conditions; (2) relics, once more widespread, from another epoch with a different climate, which are now restricted to localized habitats; (3) plants locally uncommon because they are at the edge of their range; (4) species widely distributed but occuring in very low numbers in major plant communities; (5) formerly common or widespread species now restricted to small areas left relatively undisturbed by man.

The first and second categories include a large proportion of rare plants, and these do not necessarily have narrow tolerance ranges (McMillan 1956). Edaphically restricted plants frequently grow even better on normal soils than on the soils to which they are confined. The restriction occurs because aggressive competitors that exclude them from normal soils are unable to tolerate the unusual chemical or physical conditions to which endemic plants are adapted. A moderate increase in precipitation would not normally permit regionally widespread species to thrive on the edaphically unusual sites. Therefore there is unlikely to be much change in range or abundance of edaphically restricted endemics as a result of weather modification.

The situation is different at the edge of a species' range. Rare species are often confined to special environments such as southwest slopes or mountain summits relatively drier than their surroundings. Weather modification that made these areas generally wetter would probably make conditions unfavorable for the rare species without at the same time creating other nearby favorable environments to which they might migrate (Whittaker 1967a). Since marginal populations are likely to have limited adaptive variability (Dobzhansky 1951), they cannot quickly develop adapted ecotypes. Such species are "cornered" in their present distinctive habitats and would be highly vulnerable to elimination by weather modification.

On the other hand, other marginal or disjunct populations occur where they are because they are well insulated from weather. The gorge region of the southern Blue Ridge is notable for its rich moss flora, including many endemic and disjunct species with tropical affinities. The gorges are so moist and sheltered from high temperatures that bryophyte habitats do not dry out as they do on the ridges or in the valleys below (Billings and Anderson 1966). Species that have long since been eliminated from the ridges thus remain in the gorges. Neither moderate increase or decrease of precipitation is likely to bring about wholesale loss of rare species from this protected locality.

In summary, while rare species are more likely than common ones to disappear as a result of weather modification, rarity of itself does not determine vulnerability to extinction.

Loss of Genetic Resources

The FAO Technical Conference on Exploration, Utilization, and Conservation of Plant Gene Resources, convened at Rome in September, 1967, concluded that "The genetic resources of the plants by which we live are dwindling rapidly and disastrously.

As development proceeds in the less advanced as in the more advanced areas of the world, the reserves of genetic variation, stored in the primitive crop varieties which have been cultivated over hundreds or thousands of years and in the primeval forests, equipped with a seemingly inexhaustible range of variation, have been or are being displaced by high producing and uniform cultivars, and by forest plantations. . . At a time when a continuing rise in productive efficiency is more essential than at any other for our very existence, plant breeding and plant introduction . . . are rapidly being deprived of the very raw materials upon which they depend."

Genes that confer disease resistance or other desirable attributes are sometimes found in marginal populations of plants having little value for cultivation in their own right. Some of these genes could be eliminated by weather modification. This is most likely where deliberate precipitation increase permits moisture loving species to invade exposed sites formerly too dry for them, without at the same time creating other dry habitats where the displaced species can find refuge. Genetic material of marginal populations may be lost in this way even if the morphologic species still exists.

It remains to assess the significance of the loss. Some would maintain that all genes are equally precious, for there is no way to know what might be considered vital in the future. The marginal populations that are most apt to be lost, however, are by definition those least adaptable to environmental change. They are not likely to be the ones most wanted in future breeding programs unless, as already noted, they carry genes for disease or insect resistance or other special characteristics.

Most of the important cereal crops originated in the semiarid Middle East, which is now the principal reservoir of wild genetic material of importance to breeding of commercial grains. An American effort to restrict weather modification in that area, because of possible damage to the gene pool, while encouraging it in our own territory, would rightfully be treated as a particularly intolerable form of neocolonialism.

XI. RECOMMENDED RESEARCH

Some conclusions can be based on existing information, but many unanswered questions remain about ecological effects of weather modification. There has so far not been a single field experiment completed and reported in the literature which was specifically designed to deal with any aspect of this problem. A recommendation for additional research is thus something more than the usual reflex of a scientist asked to give advice about public policy.

Research in four major categories is urgently needed before enough will be known about the ecological problem that weather modification can be generally applied with some assurance that it will not contribute to further deterioration of the environment: (1) specific field research to develop an ecological monitoring program, as discussed earlier in this report; (2) individual field and laboratory research projects to evaluate certain categories of relatively easily visualized weather modification effects; (3) large-scale cooperative research on ecosystem processes; (4) research to develop simulation models of ecosystems and to perform statistical analyses of existing data dealing with relations of plant and animal communities to weather and climate.

Many of the points in this chapter, although with different emphasis and different recommendations, are discussed in a recent report entitled "A National Program of Research for Weather Modification in Agriculture and Forestry", prepared by a joint task force of the U. S. Department of Agriculture and the State Universities and Land Grant Colleges.

LARGE-SCALE ECOSYSTEM RESEARCH

Ecological systems are inherently complex. Many practical problems of environmental change involve interactions among numerous components -- interactions which cannot be deduced from the behavior of single elements studied in isolation. Many of the ecological effects of weather modification will be system responses rather than responses of individual organisms.

The institutional structure of American science is not well adapted to deal with large scale problems of environmental quality involving complex interactions of ecological systems. Important research on environmental processes has consistently been done at universities, and the better universities normally have a wider range of competences within their faculties than most mission-oriented federal or private laboratories. Nevertheless, it is questionable whether research to develop a complex system of environmental management and control incorporating ecological and economic aspects of weather modification, air and water pollution, and similar man-induced changes can be effectively handled at universities as presently organized. As Harvey Brooks, Dean of Engineering and Applied Science at Harvard, has put it, "The development of complex systems involves the coordination of many component pieces of a problem and many individual specialties. Often it involves highly sophisticated science or mathematics side by side with rather conventional or mundane design or repetitive analysis. Such a coordinated effort tends to be incompatible with the university environment, with its high turnover of people, with its treatment of research as a part-time activity, and with the high value it places on individual as opposed to team performance, and on the proposing of new ideas as compared with critical evaluation and comparison of ideas and their execution in all the most mundane detail." Furthermore, the dispersion of effort if the necessary research is parcelled out among many universities could produce a series of inadequate solutions instead of a comprehensive plan.

It is considerations such as these that have led to the establishment of the International Biological Program, and especially to its Analysis of Ecosystems component. This is intended to be a massive ecological research endeavor carried out primarily by university investigators, but with assistance from government research laboratories. It will have its own management structure and organization. U. S. participation in IBP is not yet fully funded. When it is, it could provide a partial answer to the dilemma of how to do effective research on ecosystem processes, including those that will be affected by weather modification, making full use of competent university investigators.

The purposes of the analysis of ecosystems program are (1) to understand how ecological systems, including those disturbed to varying degrees by man, operate with respect to both short-term and long-term processes; (2) to analyze interrelationships between land and water systems so that broad regions may be considered as entities; (3) to estimate existing and potential plant and animal production in the major climatic regions of the country, particularly in relation to human welfare; (4) to add to the scientific basis of resource management, so that planning for optimal long-term land and water use can be improved; and (5) to establish a scientific base for programs to maintain or improve environmental quality.

The principles of ecosystems uncovered by the program are expected to serve as a theoretical base for designing the complex management systems needed as pressures for use of resources increase. The same principles will be the basis for dealing with some of the once slow and insidious, but now fast accelerating, changes in ecological communities as a result of man-induced environmental modification. These changes are system responses in which the visible effect often appears in one part of the system while the cause lies in another. The relation between cause and effect, and recommendations for improvement in environmental quality, would be much easier to determine if the operations of ecological systems were better understood.

Since weather modification will be a pervasive, not a localized, phenomenon, it will be linked in its effects to a variety of other environmental processes. For this reason, it is almost impossible to separate research needed to predict ecological effects of weather modification from other aspects of environmental research. This creates a problem for mission-oriented federal agencies accustomed to sponsoring investigations aimed at providing answers to specific problems in the shortest feasible time.

Agencies supporting research and development in the technology of weather modification have an obligation to support research to determine what the social and biological consequences will be if the technology they are sponsoring is perfected. In some cases at least they lack legal authority to do so. Congress and the Bureau of the Budget should insist that agencies sponsoring research in the physical science aspects of weather modification, particularly the Bureau of Reclamation and Environmental Sciences Services Administration (ESSA), allocate funds to social and biological investigations related to weather modification. These two agencies are singled out because two of the other principal agencies in the field, the National Science Foundation and the Department of Agriculture, already have mechanisms for supporting appropriate social and biological research, and the Department of Defense has wholly different reasons for involvement.

We specifically recommend that the Bureau of Reclamation, ESSA, and other agencies supporting research and development in the physical science aspects of weather modification allocate a fraction of these research funds, on the order of 2%, to general support of research on ecosystem processes related to environmental change. Funds should be assigned to the International Biological Program through the Interagency Coordinating Committee for the IBP. This departure from normal operating procedure, in which support is provided primarily for individual projects having direct relevance to the agency's mission, may require specific authorization or instruction from Congress or the Bureau of the Budget.

The recommendation of some fraction of physical science research funds, rather than a fixed dollar amount based on identified needs, is not satisfactory, but it is difficult to see an alternative. Funding agencies are accustomed to allocating money for specific projects after weighing the value of the information against the cost of obtaining it.

This is an appropriate pattern for some categories of weather modification research, but it is not applicable to multidisciplinary, multi-objective research on ecosystem processes applicable to a wide range of environmental problems.

RECOMMENDATIONS FOR FIELD AND LABORATORY RESEARCH

Artificial Rainfall Experiments

Experiments involving application of artificial rainfall to specific ecosystems should be undertaken at an early date. A suitable location for the first set of such experiments is the Pawnee Site in eastern Colorado, a major component of the Analysis of Ecosystems Section of the International Biological Program. Because of the large number of concurrent intensive biological studies proposed at the Pawnee Site, the results of the artificial rainfall experiments will be easier to interpret than if they were done in isolation.

Surprisingly, there have apparently been no experiments in which relatively small quantities of additional water have been applied to native vegetation. There are data on the response of range vegetation to flooding with large quantities of silt-laden runoff, and one or two inches per week of excess water have been applied to very small range plots in eastern Montana throughout the growing season. There have been a few experiments with irrigation of several species of forest trees, involving relatively large applications of water during a normally dry period. The application schedules did not at all simulate the moisture change that might result from weather modification, and effects of the irrigation on understory vegetation have not been reported.

There have been several reported experiments in which treated or untreated sewage effluent was dispersed in forest stands. The intent of most such experiments has been to determine how much effluent can be safely handled by the site, with little concern about effects on vegetation. A few experiments, at Pennsylvania State University and elsewhere, have endeavored to establish effluent disposal rates that would not seriously depress tree growth or that would even stimulate it. The lowest rate of application in any of these tests, however, was double the normal rainfall, and the applied effluent contained high concentrations of dissolved nitrogen and phosphorus. These experiments do not yield data useful in estimating what will happen to native vegetation as a result of a 20% increase in mean annual precipitation. Therefore the following experiment is proposed. Only the outlines are sketched here -- the details will be completed by those doing the research.

One half of each plot is to be equipped with a sprinkler system capable of delivering a relatively uniform measured application of water. (Such a system is not easy to design for plots of the requisite size -- about one-half acre.) Additional water will be applied to replicated plots at two, or preferably at three levels: 16.7% in excess of the current year's precipitation, 33.3%, and 50% in excess. An alternate pattern would be 20% and 50%. Water will be applied only during or immediately after actual storms, or at times when potentially seedable clouds are present but no precipitation occurs. This will simulate as far as possible the effects of real weather modification, and will avoid the abnormalities of applying artificial rain on sunny days. Two treatment schedules should be used, to the extent that engineering considerations make this feasible. In one, a uniform percentage increment should be added to every storm. This would presumably require automatic equipment to sense the beginning of rain; measure the amount falling in, say, each half hour; open a sprinkler valve for long enough to apply the calculated precentage of that amount; and close the valve. A second schedule would add the same total amount of water over the season, but some storms would be augmented heavily and others not at all. The augmentation pattern would be prescribed by the meteorologists associated with the project. It would be desirable to have a comparable treatment in which rainfall was decreased by an equivalent amount through a movable cover, but this would probably be more expensive than would be warranted by the information generated, at least in the beginning.

Measurements would be made of soil moisture, primary plant production, species composition, bacterial ecology of the soil, plant pathogens, decomposition of incorporated organic matter, insect and mammal activity, and other biological variables in the treated and untreated plots. All these measurements are now planned for other locations within the grassland intensive study site. Manpower and equipment would thus be available to make the necessary measurements at relatively modest additional cost. The existence of the artificially watered plots would add an extra dimension to the treatments already planned for the Pawnee Site, and would add to the value of the research on ecosystem processes for which the project is primarily designed.

Care would have to be taken in interpreting observed changes in insect and small mammal populations on the watered plots. These changes might be due to immigration from the surrounding less desirable area rather than to processes intrinsic to the plots. Artificial control might be necessary if the irrigated plots proved attractive enough to insects that their feeding would upset experimental results. Such small-plot effects are familiar to agricultural experimenters.

After a few years, in which a new equilibrium had become established, treatment should be terminated to assess the response of favored vegetation to sudden drought. Experiments combining fertilizer application with the added water should also be incorporated into the design at a later stage.

Several research proposals involving artificial rainfall have been submitted to funding agencies recently, but it is planned in most of these to at least double the normal rainfall, and inadequate consideration seems to have been given to time and rate of application, and to small plot effects. Nor have these proposals generally involved measurement of as many important biological variables as are possible at the Pawnee Site. We recommend that artificial watering experiments of the sort described here be funded directly from appropriations for weather modification research, and not as a part of the general ecosystem research support proposed in the previous section.

Controlled Environment Studies

Despite the emphasis given here to the systems nature of ecological responses, in the end it is individual organisms that are affected by weather. To predict the effects of weather modification on a particular organism, we must first know how that organism responds to environmental variables -- clear or cloudy skies, more or less rain, high or low temperatures. As the USDA Task Force on Weather Modification has stated, "We are woefully short of such information even for common plants, such as corn and wheat. Our knowledge is particularly lacking for diseases and pests, for undomesticated plants and animals, and for the reactions in the soil. This information must be obtained from laboratory environment facilities, field ecometeorological work where key variables are controlled and comparative field ecology. Although existing controlled environment facilities will be used, we will need another controlled environment laboratory devoted solely to biological responses to weather modification. Micrometeorological and biological measurement programs should be mounted to provide the information on the real plant climate and help with the translation of results from controlled experiments to the outdoors."

Many of the controlled environment studies recommended by USDA will be useful primarily for developing crop varieties better adapted to take advantage of modified weather, or to aid in assessing benefits to current agriculture of weather modification operations. In part because of the great genetic variability of many wild plants and animals, as well as the difficulty of keeping them in captivity, controlled environment studies cannot be directly translated into presumed responses of native ecosystems. Nevertheless, properly designed and interpreted controlled environment experiments can contribute to understanding of these processes to an important extent, and should be funded from appropriations for weather modification.

Field Studies of Climatic Adaptation and Genetic Variability

Field studies are needed of the adaptation of individual plant and animal species to climatic conditions. Some species exist over a wide range of climatic conditions -- these species are said to have wide ecological amplitudes. Others are confined to quite specific climatic situations. The latter are likely to respond more quickly to weather modification than those of wider ecological amplitude. There are studies of several individual species which can be used as a guide, but more such studies of important native species are required.

Relatively widespread species commonly exist as discrete or intergrading populations with different genetic constitutions. The genetic structure of plant populations, in particular, is important in determining response to environmental change. Additional studies are needed of genetic ecology in relation to environmental gradients. These investigations should initially concentrate on widespread tree species, such as some of the seed-disseminated poplars, and on important grass species, extending the work of McMillan (1959) and others.

Snow Measurement and Snow Behavior

Little is known about the spatial distribution of mountain snowpacks in relation to topography, exposure, wind, and total snow amount, except that the distribution is markedly non-uniform. This lack of knowledge is a handicap in assessing the quantitative effects of weather modification, for an observed difference in amount of snow at one or a few points is not necessarily representative of what is happening on the area as a whole. Better knowledge of the factors affecting the spatial distribution of snow would also be helpful in the design and location of telemetering devices to measure the quantity of snow on a distant watershed. These devices can be highly useful in predicting the coming season's runoff, for instance, but only if they are placed so that they properly reflect year-to-year differences in available snow. Better knowledge of snow patterns and how they are affected by snow quantity is also necessary for assessing the effect of increased snowfall on availability of forage to wildlife in winter, for predicting vegetation responses in snowbank zones, and for estimating rate of melt and release of snow added to the pack to augment runoff. Several specific research needs are evident:

1. Part of the difficulty is the lack of effective field methods for measuring the depth and water content of snow 2 to 30 feet deep. Research should be directed toward development of portable equipment for this purpose. Lightweight ground-based radar seems particularly promising. The need is for a device that will yield a snow profile along any specified line, preferably without pre-season calibration on that same line. Development of such a device would require a preliminary review of the literature, which might be completed by an interested graduate student in an electrical engineering department. Discussions with engineers indicate that the idea is feasible. If this is borne out by the literature review, a contract for developing such equipment and testing it in the field should be negotiated with a university or a commercial electronics laboratory.

2. Even lacking a reliable electronic snow measurement device, much can be done to improve understanding of snow distribution and behavior in mountain topography. At low elevations, where snow in accumulation zones typically remains on the ground throughout the winter but disappears elsewhere between storms, there is a need to determine the proportion of the area occupied by snow, and the proportion occupied by snow in excess of specific critical depths, as a function of total seasonal snowfall. This might be determined through interpretation of a sequence of aerial photographs taken at intervals between storms throughout the winter. The area covered by snow could be readily determined from the photos; field measurements might establish usable depth-area regression relations.

3. At higher elevations, where snow cover is continuous for most of the winter, recourse may be to photogrammetry (Cooper 1966). This is expensive and requires rather elaborate field calibration, but yields information about local variations in snow depth now obtainable in no other way.

4. The empirical data obtained above should be incorporated into mathematical models that define the distribution of snow in space and in time as a function of topography, total snow amount, wind, solar radiation, temperature, vegetation, and other pertinent variables. This should be approached by use of standard statistical methods, and through use of simulation models.

5. A comprehensive statistical study should be made of the data from the Cooperative State-Federal Snow Surveys These surveys have been conducted for many years in western and northeastern United States for use in forecasting streamflow. The analysis should be designed to determine the extent to which increased snow depth and water content at high elevations in years of above-normal precipitation is reflected at lower elevations. This would be useful in assessing potential effects on big game animals of deliberately

increased snow accumulations. The snow survey data would not provide a definitive answer, because it is anticipated that artificially increased snow will be more localized than the snow in a naturally occurring year of high precipitation, and because snow surveys are not regularly made in the zone of sporadic snow where wildlife are commonly found in winter. Nevertheless, the snow survey data are the best we have, and should be fully exploited. A substantial share of the data is already on punched cards, simplifying the analytical task.

Substantial research on snow distribution and behavior is already in progress, by the U. S. Forest Service, particularly in Colorado and California; the Soil and Water Conservation Research Division of Agricultural Research Service; the U. S. Army Cold Regions Research and Engineering Laboratory, and Colorado State and Utah State Universities, among others. Snow research needs to be expanded, however, and the separate investigations of different agencies better coordinated and their results more effectively collated.

ECOSYSTEM MODELS

There are several ways of making predictions about the ecological effects of an environmental change such as weather modification. The first is direct experiment: changing the precipitation inputs and seeing what happens. This has the advantage that all deductions are made from the system's actual behavior; there is no reliance on "borrowed" knowledge. The results of such an experiment are of course directly valid only for the particular ecosystem to which the changed inputs were applied. Nevertheless, a satisfactory ecological survey and classification procedure would disclose a number of other systems sufficiently similar to the one under study that results could be safely extrapolated. The principal disadvantage of a direct experimental approach to predicting the effects of weather modification is time. An impatient public is unlikely to wait the number of years required to complete an ecological experiment of this sort.

A second method is to accumulate a series of case studies of the responses of ecological systems to changes in weather and other environmental characteristics. Enough regularity may emerge that reasonable conclusions can be drawn about the general nature and direction, if not the details, of the response of similar systems exposed to deliberate weather change. This sort of argument from analogy has formed the basis of most of the present report.

An extension of the essentially qualitative and verbal comparative analysis of case studies is the statistical screening and analysis of large bodies of observational data on environmental variables and associated biological responses. The concurrent development of high speed computers and of statistical methods such as stepwise multiple regression and principal components analysis has made it possible to identify functional relationships that were not previously apparent. Additional research is needed to extend the capability of these methods. However, existing procedures, applied to existing data, may lead to significant conclusions about anticipated responses of ecosystems to environmental change. An effort to identify and analyze relevant data in the files of government agencies and elsewhere should be a part of a weather modification research program.

A third approach, utilizing some of the same mathematical techniques as the last but conceptually distinct, depends on structural models of the matter and energy budgets of functioning ecosystems. Incorporated into these models are the physiological effects on plant and animal populations of the principal environmental factor-complexes -- moisture, nutrients, heat, and light -- and the feedback mechanisms which regulate the size of each population. Such structural models are abstractions which may in the long run lead to better understanding of our universe. They can be of great value even when wrong, for the process of proving them wrong often provides new insights into areas to be explored and new experiments to conduct. Computer models are particularly well adapted to dealing with problems that are presently beyond the range of analytical solution because of their size and complexity, or because they cannot be solved effectively in the time available by experimentation on actual systems. Full-scale ecosystems have both of these characteristics.

Although it may start from simple verbal statements or block diagrams expressing the relationships among components, an ecosystem model will quickly evolve into a set of mathematical equations and statistical probability distributions representing rates and time series of input and output of energy, water, and mineral elements; rates of transfer of these factors within the system -- from soil to plant, plant to animal, and the like; and impacts of specific environmental processes on flow rates. Ecosystem models will of necessity have to be designed for computer usage, since digital or analog computation is the only technique known today that can adequately represent the complex interactions of a dynamic and constantly varying ecosystem.

The development of system models proceeds in several stages. They are initially built up from simple mathematical statements and statistical distributions which represent functions and interrelationships derived from measurements on real systems, or from plausible estimates where data are lacking. These statements are translated into computer language, permitting simulation of system behavior on the machine. The results of this simulation are compared with the outcome of concurrent experimentation and observation in the real world; points of agreement and divergence are examined to refine and improve the model, and to identify aspects of the system about which more empirical information is needed. System modeling is thus a continuous circular feedback process linking field measurement and observation with computer simulation, or with such mathematical optimization procedures as linear and dynamic programming.

The information necessary to specify the relationships between components and to make preliminary estimates of the rate coefficients will come from prior knowledge available in the literature and in the experience of the modelers. The relationships need not be exact to be useful. They only have to be close enough to give better results than could be obtained by common sense alone. This is because the behavior of the whole is dominated by the pattern of connections between the component parts and processes, rather than by the exact nature of any one component.

The preliminary model is then run or experimented with to arrive at deductions regarding the system. The initial model specifies rates of flow only at one brief instant. As time passes, the stock of matter or energy in the various components changes as a consequence of flows in and out. The soil dries, and vegetation is grazed. Flow rates, which depend upon the component quantities, change accordingly. It is necessary to use mathematical equations or a simulation program to indicate what these changes will be, since unaided intuition cannot cope with simultaneous changes in a large number of interacting components.

An important use of system models is to determine the relative sensitivity of the system to variations in specific inputs. Sensitivity analysis can help to determine the limits within which management practices or other inputs can be varied without causing appreciable deterioration in system performance. It can also help to spotlight those aspects about which more needs to be known before system performance can adequately be predicted. Much orthodox scientific thought has held that all aspects of a system must be understood before real progress can be made; sensitivity analysis leads to concentration on the truly pertinent aspects of a system's behavior.

The particular type of sensitivity analysis to be employed depends on the mathematical structure of the system model. The model will usually be a computer simulation program of some kind.

Each of the parameters in such a model can be varied in succession, while the others are held constant. The output of the simulation program is followed for different values of each successive input variable. It may develop, for instance, that the output changes only slightly as some input such as precipitation is progressively changed within a particular range. As a threshold is exceeded, however, further changes may produce important changes in output.

Forms of sensitivity analysis other than simulation are often preferable where the mathematical formulation of the model permits. In particular, if the system or an important subsystem can be formulated as a linear programming problem, powerful and efficient tools of sensitivity analysis based on mathematical optimization procedures are available.

It is commonplace that computer models are only as good as the data that go into them, and only as good as the underlying functional relationships upon which they are based. Ecological knowledge is deficient in both respects because of the large number of species and the complexities of the ecosystem relationships with which ecologists deal. Active field research and data collection must accompany intensive efforts at model construction. Ecological models are principally useful for suggesting fruitful lines of field research and for eliminating unfruitful hypotheses; they are in no sense an end in themselves. It is recommended, however, that substantial weather modification research funds be allocated to development of ecosystem models useful for predicting certain classes of effects from this form of environmental alteration.

Existing and Proposed Computer Models

There is no one best model of anything, only models better or worse for particular purposes. In particular, no single model can simultaneously meet all the requirements of generality, precision, realism, and tractability or ease of manipulation. Several computer models useful for research on ecological effects of weather modification are in various stages of development. Additional effort is needed to produce others.

The Stanford Watershed Model (Crawford and Linsley 1966) is designed to imitate the hydrologic behavior of small stream basins under varying inputs of precipitation, solar radiation, and other climatic variables. The primary outputs are streamflow, in the form of a simulated hydrograph of mean daily flow; soil moisture storage; and actual transpiration. Streamflow can be calculated at several points along the main channel, resulting in separate hydrographs representing runoff contributions from specific portions of the basin. Infiltration, interception, and related influences of vegetation and land use are read in as data; there is no attempt to simulate the dynamic ecological processes that might alter the response of the catchment over time. Close agreement can be obtained between simulated and observed hydrographs in particular basins.

The Stanford Watershed Model is particularly useful for predicting the effect of changes in precipitation input on changes in total streamflow and its time distribution. The effect on streamflow will depend both on the weather modification strategy used in the simulation and on the preexisting climate. As expected, simulation trials with the Stanford Model show that the greatest change in streamflow as a result of a fixed percentage increase in precipitation is in years of above normal moisture.

The Stanford Model, with its emphasis on calculation of streamflow regimes, is likely to find its greatest ecological application in assessing effects of weather modification on stream fisheries sensitive to flow rates and in testing the consequences of major climatic alterations such as hurricane control along the eastern seaboard.

A simulation program under development at the University of Michigan by the senior author of this report is a more detailed model of the transpiration and soil moisture component of the Stanford Watershed Model. This program evaluates the disposition of precipitation by the soil and vegetation at a point, rather than integrated over an entire stream basin or sub-basin. Water leaving the root zone is a final output from the program; there is no attempt to route runoff to stream channels as in the Stanford Model.

The program computes actual transpiration, transpiration deficit, mean soil moisture, and total runoff for any specified rainfall regime. Results are printed by semi-monthly periods. Precipitation is then increased by a small amount to evaluate the disposition of additional rainfall such as might result from weather modification. The additional moisture can be distributed over the entire year or allocated to certain seasons. This calculation gives the proportion that appears as runoff and as transpiration -- in effect the marginal return to runoff and transpiration from precipitation.

The program requires real or simulated data on total daily precipitation and net radiation, and mean daily air temperature, relative humidity or vapor pressure, wind speed, and average cloudiness. Other data required are elevation above mean sea level, aerodynamic roughness of the vegetation surface, reflectance coefficient of the surface integrated over the whole shortwave radiation spectrum, longwave emissivity of the surface, total waterholding capacity of the soil profile, and texture of the soil (sand, loam, or clay).

Much more complex models are to be developed in the course of the IBP Grassland Biome research. Five levels are contemplated: individual ecological processes, ecosystem components, a model of the Pawnee site, a regional grassland model, and a general grassland biome model. In going up this hierarchy of models, generality increases but precision decreases. Some of the submodels are mineral cycling (nitrogen, phosphorus, sulfur); plant community structure; animal social interactions, within and between species; photosynthesis and respiration models (broken down by community types); animal metabolism; hydrology; system food chain -- "who eats whom"; and atmospheric models that generate forcing functions for the other submodels.

The broad objectives of the grassland research are to study various states of grassland ecosystems in such a way as to determine the interrelationships of structure and function, and to determine the variability and magnitude of rates of energy flow and nutrient cycling. The results will be encompassed in an overall mathematical model which will reflect the responses of the system to various natural and man-induced stresses. This research is barely started; useful predictions are some years away. As it progresses, it will yield information increasingly valuable for predicting specific ecological effects of weather modification, not just in grasslands but in other community types as well. Substantial support toward developing additional ecologishould be provided from weather modification research funds. It is not yet possible to point to truly successful predictive simulation models in ecology, at least not to the extent that this can be done in the transportation or oil industries, for instance. Weather modification has promise of being among the first areas in ecology where real success in system modeling can be achieved.

Most simulations so far attempted in ecology have dealt chiefly with predation, or with other population interactions involving transfers of matter or energy among identifiable compartments. Individual organisms have been treated as indistinguishable atoms whose mass responses could for practical purposes be described by deterministic differential equations.

This modeling strategy will not work in the case of weather modification -- at least not at the level of models accepting rainfall or other weather variables as direct forcing functions. Weather is to a great extent an on-and-off phenomenon. Strong reliance will have to be placed on discrete models, on stochastic processes, and on Monte Carlo methods to define the statistical distributions of biological outputs from normal and modified weather.

Time Distribution of Climatic Variables

Both the existing relatively simple water use-streamflow models and the more complex ecosystem models eventually to be developed through the IBP will require data on precipitation and other climatic variables as inputs or forcing functions. In most ecological simulations, it will be necessary to operate the model over a long span of simulated time in order to generate a probability distribution of outputs -- a form of Monte Carlo procedure. If application of simulation analysis using computer programs of the Michigan and Stanford type is not to be restricted to the relatively few places having adequate climatic stations, and to the relatively brief span of the historical record, there must be some means for generating long traces of synthetic climatic data.

Annual rainfall amounts typically show so little persistence or serial correlation that acceptable sequences of annual rainfall can be synthesized with a simple random number generator. However, annual totals are of little value in the complex models discussed here. The random number approach fails for the shorter time periods used in detailed simulation. Single-lag Markov chain models and linear autocorrelation schemes fail to reproduce the characteristics of existing rainfall records. Methods based on probability distributions of the time between storms and of storm duration; on multivariable, multilag correlations; and on observations from weather satellites, are being developed by Peter S. Eagleson and associates at MIT, by Myron B. Fiering and associates at Harvard and by ESSA Research Laboratories, among others. Relatively satisfactory procedures should be available in the near future for generating synthetic sequences of daily or hourly precipitation at any desired point on the globe. Research to this end should be given continued support.

The general procedures used to generate acceptable precipitation traces should also yield usable sequences of humidity, solar radiation at ground level (as affected by cloud cover and atmospheric conditions), and other climatic data needed in simulation models, although less has been done with these than with precipitation. Weather satellite observations seem particularly promising for solar radiation studies.

A major difficulty is the lack of suitable methods for generating simultaneous synthetic traces of cross-correlated weather variables. Substantial errors are inevitable if, to take an extreme example, synthetic precipitation and solar radiation traces are generated wholly independently of one another. Better methods are needed to correlate these sequences in time.

It would also be desirable if meteorologists directly concerned with weather modification were to provide ecologists with an effective model of the raindrop size distribution and impact velocities expected from modified and unmodified storms. This is vital information for analysis of the effect of raindrops on soil and erosion in semiarid grasslands, for instance.

Large Scale Data Analysis

Government and other organizations have over the years gathered great quantities of biological data, primarily for administrative purposes. Examples are the range surveys conducted by the U. S. Bureau of Land Management and its predecessors since the mid-Thirties, and by the Forest Service even earlier; wildlife census data obtained by state game and fish agencies; insect surveys made by U. S. and Canadian agricultural and forestry organizations; and of course the weather data accumulated by the U. S. Weather Bureau and its sister agencies in other countries. These data have typically been collected over long periods of time, by means of sampling procedures having a low level of repeatability. Such data are of relatively low precision, and often have considerable bias. They are of value not because of the reliability of any single observation, but because of their enormous total number. The signal to noise ratio is sufficiently low that it would be difficult to detect meaningful relations through conventional statistical analyses performed on small data blocks of the size commonly used in ecological research. The great mass of data, however, might allow detection of broad patterns when all the data are pooled. This can be done only with modern high-speed computers. The computer not only makes it feasible to detect patterns in noisy data, but it is the key to the even more difficult task of finding how far the patterns depart from those which would have been expected by chance alone. Thus the computer offers, for the first time, the possibility of hunting for and finding hidden underlying relationships in the vast masses of data on population fluctuations and epidemics which have been routinely collected over the years, but in which there may be substantial errors of measurement (Watt, In Press).

An effort may be justified to screen existing data for patterns relevant to predicting ecological effects of precipitation modification. A principal problem will be to locate and identify the data. There was insufficient time during the preparation of this report to query government agencies and others to this end. A second problem will be to ask the right questions, and to design the analysis so as to answer them. Most difficult, though, will probably be the coding of the available data and its reduction to a form acceptable by the computer. The cost of the entire operation may well outweigh the potential benefit. A small university research group, however, should be engaged to make a preliminary national inventory of biological field survey data, and to assess the desirability of an extensive statistical screening project.

PALEOCLIMATOLOGY AND PALEOECOLOGY

The study of fossil plant materials often permits reconstruction of past vegetation. Since climate is a major factor in the development of plant cover, information about past climates can often be gained from this knowledge of vegetation. Animal remains and human artifacts may yield other clues about past conditions. The Ecological Society (1966) report stated that the fossil record is particularly valuable in anticipating the potential ecological effects of weather modification, because it gives us our only information about the biological results of major climatic changes on a global scale. The panel pointed out that use of these data is hampered, however, by a lack of independent information about the actual physical changes in climate that were involved, so that much investigation of these changes consists of an attempt to infer climatic changes from the biological evidence, rather than determining the way in which organisms have been influenced by climate.

A thorough survey of the pertinent literature on paleoclimatology and paleoecology was prepared for this report by Val L. Mitchell of the Center for Climatic Research at the Universtiy of Wisconsin, and reviewed by senior members of that Center. Mitchell concluded that the specific information needed to infer vegetational changes which might result from a precipitation change caused by proposed weather modification acitivies is not currently available from paleoecological sources, nor is it likely to be in the near future. Reasons include (1) the fact that unlike artificial weather modification, natural precipitation change is usually confounded with temperature change; (2) the fact that temperature, rather than precipitation, has been emphasized in paleoecological studies; (3) the generality of information obtainable from the fossil record -- the best that can be said is that one period was wetter or drier than another; and (4) the degree of circularity involved because of the scarcity of paleoclimatic information from sources other than paleobotany.

Because of the essentially negative conclusions of Mitchell's report, with which we concur, it is not printed in its entirety here. We do not recommend that extensive research in paleoclimatology and paleoecology be funded from appropriations for weather modification.

MICROCLIMATOLOGY

Scientists and administrators concerned with agricultural applications of weather modification have urged a substantial effort to characterize more fully the physical environment of plants, and to define natural and man-induced changes in crop environments. They have recommended a program of detailed measurements of the physical microenvironment of leaves in different crop canopies under different climatic and management conditions. This information is deemed necessary for evaluating the response of crop plants to changed water and radiation supplies and for assessing the hydrologic effects of weather modification in croplands. The suggested research involves investigation of energy, carbon dioxide, light, temperature, and water relations of individual leaves and groups of leaves.

Information of this sort will eventually be of great value in making agricultural adjustments to get maximum benefit from deliberate weather modification. It will be of less use to those concerned with probable responses of uncultivated plant communities to the kinds of weather modification now foreseen. Ecologists and foresters will continue to be grateful for additional information about microenvironmental processes in individual leaves, plants, and stands, but extensive additional research in this area cannot be justified at this time solely on grounds of its value in predicting ecological effects of weather modification on natural or semi-natural ecosystems.

RESEARCH TO DEVELOP OPTIMAL STRATEGIES FOR INCORPORATING WEATHER MODIFICATION INTO RESOURCE MANAGEMENT

There is a marked tendency in American life for each new technological innovation to be viewed as an end in itself. Weather modification will probably be no exception. If the technology should be fully developed, it is likely to be applied without much regard for alternative means of achieving the same end. There is an urgent need for policy and planning research to develop guidelines for most effectively incorporating weather modification into the repertory of procedures available for management of natural resources.

Increased production from native rangeland is likely to be a somewhat less important economic objective of weather modification than some other applications such as augmenting runoff into water supply reservoirs. Nevertheless, the problem of incorporating weather modification into range management strategy may provide some useful insights.

The demand for augmented precipitation for use directly on semiarid land is almost certain to be greatest on marginal croplands where production of cultivated crops such as wheat is uncertain and erratic because of the frequency of drought years. Government subsidies are now a potent factor in preventing return of much cropland acreage to range forage production. Agronomists, soil scientists, grassland ecologists, and agricultural economists have been almost unanimous in proclaiming, since even before the great drought of the Thirties, that the Great Plains region should be devoted primarily to stock raising. Crop production should supplement livestock production rather than compete with it. There is likely, however, to be a strong temptation for farmers and ranchers to use the prospect of artificial precipitation increase as an excuse for attempting to increase production of cash grain and supplemental livestock feed. It has frequently been shown that the greater the amount of supplemental feed available, the greater the likelihood that associated rangeland will be overused. The more supplemental feed, the more animals can be carried through the time of non-grazing, to go onto the range during the season when range forage is available.

These facts lead to the conclusion that if weather modification cannot appreciably increase precipitation in the driest years, it will be an added inducement for improper land use by further encouraging the conversion of rangeland to cropland during the wetter years, when weather modification will presumably be most effective. The result would be increase in wind erosion and in acreage of crop failure in drier years.

If conversion of natural rangeland to crop production can be prevented by a combination of education, regulation, incentive payments, and other means, both individual ranchers and the national economy could benefit through increased forage production in non-drought years provided that ranchers can and will make necessary adjustments in livestock numbers to protect the range during low rainfall years. There are abundant data to show that up to now such adjustments have not been made voluntarily until deep in a drought. By then the range resource is usually severely damaged.

If weather modification only made the wetter part of the climatic cycle still wetter, and provided no appreciable additional precipitation in the driest years, overstocking in drought years would in all probability be increased. There would be accelerated deterioration of the range resource from overuse in dry years and from deposition of dust from adjacent cultivated land on which crops failed in dry years.

Range fertilization might be effectively combined with weather modification to increase total economic return. Fertilization is in general most effective in years with above normal rainfall. A moderate increase in precipitation might turn range fertilization from a losing to a profitable operation in some areas.

The point of these examples is that substantial research is required to determine the optimal strategy for combining weather modification, range fertilization, adjustments in livestock numbers, and cropping patterns for supplemental feed, to name only a few available management tools. Some conclusions are obvious: simply increasing livestock numbers in anticipation of increased forage from weather modification would be disastrous. Only slightly less so would be a strategy that concentrated on increasing forage yield in the wetter years, without considering what would happen during the inevitable drought. Other possibilities are less clear. Advanced team research is required, involving simulation of typical ranch enterprises under various management assumptions and inputs, use of linear and dynamic programming models where appropriate to determine optimal solutions, and related efforts. An important part of this program must be sociological research to help ensure that people accept the management recommendations.

Development of appropriate management strategies will be equally complex in water source areas. Initially, policy has been to attempt to increase inflow into water supply reservoirs during low runoff periods. Cloud seeding operations are to be interrupted when water levels reach the mean or median for that time of year. Since runoff is basically a residual after evaporative losses, however, the greatest payoff in water yield per unit of weather modification effort will surely come in years of high precipitation. These are just the times when additional rain or snow may be most harmful to other interests.

Alternative methods of alleviating temporary or continued water shortage, real or imagined, include transbasin diversion, desalination, reduction of evaporation and seepage from reservoirs and channels, reduction of evaporation and transpiration by vegetation on water source areas, and reduction of uncertainty about future supply through improved streamflow forecasts. Intensive research, again involving many of the methods previously discussed, is required to develop the most desirable combination of these approaches. Such research is likely to be strongly inhibited or opposed, because each of the separate component water management techniques is the province of a separate group within government or society. Each will therefore tend to advance its own solution to the problem instead of cooperating in development of a strategy to optimize social benefits from the whole system.

All these points indicate that research is needed to develop a resource management model that will specify the consequences of a given set of management strategies, perhaps including weather modification, within certain probability limits. The model should indicate when these consequences will occur and who will be affected. It should suggest how the benefits and costs are likely to be distributed; this in turn may help to indicate who should be responsible for making the investment. Sets of reasonable alternatives, derived from the predictive model, can then be formulated and presented for political decision. The broader the array of opportunities set up for exploration, the greater the final range of choice will be. We do not yet have the information, either from ecology or from economics, to specify all the available opportunities for constructive use of the environment.

There is an urgent need for close collaboration between ecologists and economists to develop generally acceptable methods of measuring and evaluating environmental quality. Modern resource economics is primarily concerned with the relation of resource use and allocation to social welfare in the broad sense. It can provide important insights to guide planning for maintenance and enhancement of environmental quality. An extensive cooperative research effort, involving both ecologists and economists, is necessary if this is to be accomplished. Even modest success in constructing an economic model for environmental quality would be beneficial by lending rigor to the arguments of those opponents of uncontrolled environmental change who are accused of inconsistency when they say "So far but no farther". It can help to resolve conflicts over the relative amounts of environmental modification that should be encouraged or permitted in different situations, and it should help to specify the social consequences of a given set of management decisions within certain probability limits.

XII. LOCAL PRE-MODIFICATION SURVEYS

An essential part of the planning process for any form of weather modification is a pre-operational survey of each target area, to identify and evaluate biological and social conditions likely to be significantly altered by a deliberate change in climate. This pre-operational survey is distinct from monitoring studies carried out over time to measure induced ecological change. The expense of a preliminary regional survey is as much a part of the cost of a weather modification program as the purchase of cloud seeding agents.

The public is entitled to know that an effort has been made beforehand to identify wildlife populations, fishing streams, and other environmental and amenity values that might be affected, beneficially or detrimentally, by weather modification wherever it is contemplated. How prospective environmental effects should be weighed against presumed economic benefits is primarily a matter for political decision. Such decisions can be made rationally only if the requisite information is available.

Because target areas will differ in climatic characteristics and associated biological attributes, and because preferred weather modification strategies may vary from place to place, individual surveys will have to be made in each target area. For the same reasons, no blanket prescription can be written for the conduct of the surveys, but some general guidelines can be suggested.

SURVEYS TO ACCOMPANY THE UPPER COLORADO RIVER PILOT PROJECT

Plans are being completed for an extensive operational test of cloud seeding techniques to augment runoff in the Upper Colorado River Basin. Officially described as a pilot project, it is planned to last several years and to cover several thousand square miles. Controlled statistical tests will be made of the effects of weather modification -- specifically, cloud seeding to increase winter snow accumulation.

A concurrent biological survey of those parts of the Colorado River Basin to be covered by the weather modification tests should be an integral part of the pilot project. This is not because significant ecological (or social) effects are anticipated from the pilot test itself, which will involve seeding only a portion of the potentially seedable storms, and which is planned for only a relatively few years. Rather, the pilot biological survey should be started now for exactly the same reason that the pilot meteorological program is being undertaken -- to develop and test techniques and procedures for use in an eventual operational program.

It will be argued that it is pointless and unnecessary to develop procedures for pre-operational biological surveys until it is more fully demonstrated that deliberate weather modification is indeed feasible. This is specious reasoning. If the prospects of deliberate weather modification are good enough to justify research operations on the scale of the proposed Colorado Pilot Project, they also justify expenditures to develop procedures for identifying in advance some of the possible biological and social consequences. To put this another way, agencies contemplating operational weather modification programs should be compelled to get into the habit of including biological surveys in their planning from the beginning.

Conservation organizations, sportsmen's clubs, and other citizens' groups in and out of the Colorado River Basin should act through their elected political representatives to ensure that a large scale weather modification pilot project is not undertaken in the region unless funds and manpower are provided for a concurrent biological pilot survey. It is reasonable to suggest that 10% of the total cost of the pilot project be made available for development of ecological survey procedures.

COMPONENTS OF A PRE-MODIFICATION SURVEY

The emphasis in this section is on the organization of a preoperational survey, rather than on the details of what should be examined. Specific elements will differ accordingly as the proclaimed objective of the weather modification program is increased snow accumulation, for instance, or augmented spring and summer rainfall for the benefit of livestock producers.

Much of the necessary information is already available in the files of government agencies and elsewhere. The first task is therefore to compile and collate existing data. This should then be supplemented as required by investigations in the field.

Preliminary office data compilation

1. Delineation of treatment unit. The basin or other land unit to be surveyed should be of appropriate size for meteorological treatment and for ecological evaluation.

2. Topographic and climatic data. The proportion of the treatment unit occupied by each principal elevation class should be determined from U.S.G.S. maps and other sources. In mountainous areas it will usually be necessary to separate predominantly north-facing slopes from south-facing. Climatic data (usually correlated with elevation) should be similarly compiled to determine the proportion of the treatment area in each principal climatic zone.

3. Land use data. The records of the U. S. Soil Conservation Service and the U. S. Forest Service are likely to be the best initial source for data on present land uses within the treatment area. Specific land use problems are highlighted for each state in the Conservation Needs Inventory Reports prepared by SCS. Generalized land use surveys and maps have been prepared by SCS for most counties in the U. S.

4. Ecological land classification. In non-cultivated and non-forested areas, range site maps prepared by SCS are likely to be particularly useful for distinguishing areas in private ownership that are potentially sensitive to weather modification from those likely to be relatively insensitive. These maps are based on range site criteria developed by E. J. Dyksterhuis for the Northern Plains States, but the principles are useful elsewhere. Somewhat similar maps of publicly owned land are prepared by the Forest Service and the Bureau of Land Management.

The first seven range-soil groups included in the SCS classification are more productive than ordinary upland ranges because of superior soil moisture availability. Natural topographic features frequently govern this moisture availability to such an extent that additional moisture yielded by weather modification, at least during the growing season, is likely to have relatively little ecological effect on vegetation. This would not necessarily be true if winter snow were to lie longer on the ground, however. These seven groups include:

a. Wet land: Marshy lands where seepage and ponding raise the water table above the surface during a part of the growing season. Too wet for cultivated crops but too dry for common reed, cattails, or true aquatics. Additional precipitation that appreciably increased the water supply to such areas could have a significant effect on animal populations, but probably not on the vegetation.

b. Subirrigated: Lands with water table rarely above the surface during the growing season but subirrigated during most of the growing season. Not very sensitive to weather modification so long as subsurface drainage conditions are not markedly changed.

c. Saline subirrigated: Subirrigated lands where salt and/or alkali accumulations are apparent and halophytes occur over a major part of the area. Sensitivity to weather modification could arise here if there was enough additional leaching to carry away a substantial part of the salts, or to concentrate salts in portions of the area.

d. Overflow: Areas regularly flooded, whether by stream overflow or by run-in from higher slopes.

e. Saline overflow: Regularly flooded areas where salt or alkali accumulations occur and halophytes occupy a major part of the area.

f. Sands: Deep, loose, fine sands on nearly level to undulating relief. Does not include compact dark, nearly level loamy fine sands, or loose medium and coarse sands.

g. Savannah sites: Uplands on which grass cover with isolated trees is the normal or climax vegetation (at least as defined by the SCS surveys). This should not be confounded with the savannah type of cover which results from overgrazing of natural grassland or the cutting of natural forest land. This site is common at margins of forest climates. Within grassland climates it occurs where soil moisture relations especially favor tree growth (SCS Technical Guide). Because savannah sites, as defined by SCS, occupy an apparent climatically controlled tension zone, they may be particularly sensitive to weather modification.

The second principal category in the SCS classification is ordinary or normal upland soils with gentle relief and no obvious soil factors inhibiting vegetation. The vegetation can make a normal response to the climate of the region. These sites, well adjusted to the pre-existing local climate, are likely to be particularly sensitive to weather modification. As defined by the SCS, these include (a) sandy, (b) silty, and (c) clayey soil sites.

The third range site category is uplands with inhibitory soil factors which prevent development of the regional climax. These include a variety of situations, in many of which the primary vegetation control is apparently not weather. These are for the most part likely to be relatively insensitive to weather modification, but there will be exceptions. The characteristics of each site in this category should be evaluated separately, to define any that may be particularly sensitive to climatic change.

Somewhat similar data can be obtained on lands within the treatment unit, from the files of the U. S. Forest Service or the appropriate state forestry agency. Advantage should also be taken of appropriate ecological research papers, for example, those of Marr (1961) and Miller (1965) in the high country of Colorado.

5. Animal data. State game management agencies should be consulted to determine the number and general condition of large mammals. For each herd or other defined animal grouping, the area used for summer range and for winter range should be identified. The extent and condition of these ranges will generally already have been estimated by the state agencies concerned. Time of availability of summer range is important in case artificially increased snow accumulation should delay the time that summer forage becomes available, thus adding to pressure on the winter range. Such an animal survey should recognize that discrete animal groupings usually have relatively predictable yearly patterns of movement. Each such grouping has its own separate winter range and summer range.

6. Wetlands. Where significant areas of wetlands occur, they should be identified and their water supply conditions evaluated with respect to anticipated changes resulting from weather modification.

7. Pests and diseases. County agricultural agents, state university agricultural experiment stations, personnel of the U. S. Forest Service, U. S. Agricultural Research Service, and others familiar with the local situation should be consulted for their opinions as to the likelihood of pest outbreaks as a result of the postulated weather change. At the present time, the knowledge of experienced entomologists and pathologists directly familiar with the treatment area seems the best means of spotlighting potential trouble.

8. Stream survey. A survey of the existing stream fishery resources of the treatment area should be made. This would necessarily involve both a compilation of existing data and a field survey.

9. Avalanche and snowslide data. Areas of frequent snowslides are likely to be relatively sensitive to weather modification (and may indicate the success of the weather modification program itself). Records of state highway departments concerning frequency of blockage by snow of highways kept open during winter may be useful.

10. Predicted additional accumulation of snow and of resulting runoff by elevation zones. The postulated impact of the weather modification program itself on the precipitation of the treatment area should be mapped, by elevation and climatic zones.

The results of the data compilation program will reveal points of possible sensitivity about which more information must be obtained from field surveys covering at least the following points:

1. Aerial photographs. Air photos should be obtained in late spring when multiple-purpose air photos are seldom made, because remaining snow obscures vegetation and other features. Aerial maps at this time, however, will indicate much about where snow is presently accumulated and will provide a guide to anticipated changes resulting from increased accumulation. Admittedly, such a set of photos obtained on only one date is a biased sample, but the average snow conditions can be correlated with data from the SCS regional snow surveys to indicate whether snowpack at the time of photography is above or below normal.

2. Supplementary data not available from office data compilation. No specific recommendations for the conduct of these surveys are made here. Determination of such procedures should be a major objective of the proposed pilot biological survey in the Colorado River Basin.

3. Erosion hazards. Close attention should be paid to erosion hazards, particularly at lower elevations. This applies especially to the lower reaches of streams, originating in high country where weather modification is carried out, but flowing through lower elevation areas with erodible streambanks. This situation might be acute if the stream was not regulated by upstream storage reservoirs.

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ABSTRACT

If deliberate modification of weather can be achieved, the structure of plant and animal communities will be altered through shifts in rates of reproduction, growth, and mortality of weather sensitive species. Ecological changes will generally require several years to become fully evident. Weather modification may interact with other ecological stresses such as air pollution and pesticide application to produce changes greater than the sum of the individual effects. The fallacious argument is rejected that because the change anticipated from weather modification is smaller than the normal variability of weather, weather modification will have little or no biological effect. Catastrophic outbreaks of weeds or insect pests are unlikely as a result of weather modification, but not impossible. Big game animals could be adversely affected if snow accumulation is significantly increased on winter range. Somewhat different effects are anticipated in semiarid and in humid regions. There does not appear to be an immediate serious threat of environmental contamination from silver iodide or other seeding agents. A global environmental monitoring system is urgently needed but adequate planning for such a system has not yet been done. A monitoring system should deal with all forms of environmental change, not weather modification alone. No research dealing specifically with ecological effects of weather modification has yet been reported. Agencies sponsoring research and development in the technology of weather modification have an obligation, which they have so far not adequately met, to support research to determine the social and biological consequences of this technology. Institutional arrangements may have to be altered to require such research support. The report includes sections on anticipated kinds of weather modification; effects in semiarid climates and in humid climates; pests and diseases; direct effects of seeding agents; biology of lakes and streams; fog, hail, lightning, and hurricane modification; environmental monitoring programs; inferences from ecological theory; recommended research; and recommended pre-modification field surveys.

KEYWORDS
Weather modification/plant ecology/animal ecology/ wildlife/aquatic habitats/silver iodide/insect invasion/weeds/plant diseases/monitoring/research design.